Gordon

A PHYSICAL TREATISE

ON

ELECTRICITY AND MAGNETISM.

VOL. II.

A PHYSICAL TREATISE

ON

ELECTRICITY AND MAGNETISM.

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A PHYSICAL TREATISE

ON

ELECTRICITY AND MAGNETISM.

Part III. (*continued.*)

ELECTRO-KINETICS.

CHAPTER XXX.

ON STANDARD COILS.*

In all absolute measurements it is necessary to know what are called the "constants" of the instruments.

In measuring currents by galvanometers it is necessary to know accurately the number of windings, and the size and position of each. In order, then, that the windings may be accurately counted, and measured directly, and that small errors of measurement may not introduce a large percentage error, it is necessary that the coil should be large, and should contain only a few layers of wire.

In constructing a sensitive galvanometer it is necessary to arrange the coils so as to produce the greatest possible effect on the needle, and, therefore, the wires must all be as near to the needle as possible, and there must be a great number of them.

In other words, the coil must be small, and with a great number of turns all crowded close together.

Thus the conditions to be satisfied in making a standard galvanometer are quite different from those required in making a sensitive galvanometer. On this subject Professor Maxwel says,†—

* Maxwell's "Electricity," vol. ii. ch. xv. p. 312.
† Ibid., 707, vol. ii p. 312.

"In constructing a sensitive galvanometer we aim at making the field of electro-magnetic force in which the needle is suspended as intense as possible. In designing a standard galvanometer we wish to make the field of electro-magnetic force near the magnet as uniform as possible, and to know its exact intensity in terms of the strength of the current."

On account of this difference the constants of sensitive galvanometers are not determined by direct measurement, but by electrical comparison with large standard coils.

To determine the values of the deflections of a sensitive galvanometer we proceed as follows :—

We place it concentric with a standard coil, and with its coils parallel to the coils of the standard. The latter being large, the sensitive galvanometer will go inside it. The plane of the coils is placed in the magnetic meridian. We then send currents, whose ratio is known, in opposite directions through the galvanometer and the standard coil. Suppose we make the direction such that the current in the galvanometer tends to deflect the needle, and that in the coil to bring it back to zero.

Let δ be the deflection,

C the current in the standard coil,

c the current in the sensitive galvanometer,

H the earth's horizontal force at that time and place,

$2\ l m$ the magnetic moment of the needle.

Also let Γ be the couple of the coil with a unit current on a needle of unit moment. Then, if we are experimenting with the large coil only, and the sensitive galvanometer be removed, Γ will be the number by which H $\tan \delta$ must be divided to obtain the true strength of the current; and as the ring is large, this number will be equal to $\frac{2\ \pi}{a}$ times the number of windings.

Let γ be the corresponding quantity for the sensitive galvanometer.

This will not in general be proportional to the number of windings, and a cannot be measured directly.

Let the sensitive galvanometer be replaced.

The couples acting on half the needle now are—

Tending to deflect it as long as the diflection is very small,

$$c\ \gamma \cos \delta\ .\ l\ m.$$

Tending to bring it to zero,

$$C\,\Gamma \cos\delta \,.\, l\,m \text{ and } H \sin\delta \,.\, l\,m.$$

When the needle is in equilibrium we have

$$C\,\Gamma \cos\delta + H \sin\delta - c\,\gamma \cos\delta = 0,$$

or dividing by $\cos\delta$

$$C\,\Gamma - c\,\gamma = H \tan\delta.$$

If we vary the ratio $\frac{C}{c}$ till $\delta = 0$, that is, till the needle comes to zero, we have

$$\gamma = \frac{C}{c}\Gamma.$$

The ratio of C to c is found without knowing either C or c, by dividing the same current into two circuits, and interposing resistances R and r in C and c respectively. Then if G is the resistance of the standard coil and g that of the small galvanometer, we have

$$\frac{C}{c} = \frac{r + g}{R + G}$$

and so γ is known.

For further information about the comparison of coils, the reader is referred to Maxwell's "Electricity," vol. ii. ch. xvii.

Electro-Dynamometer.

The great electro-dynamometer of the British Association, Plate XXVII., may be taken as a specimen of a standard coil. It is at present deposited in the Cavendish Laboratory at Cambridge.

It consists of two coils placed parallel, and ½ a metre apart. The mean radius of each is ¼ metre, and each consists of 15 layers, each containing 15 turns of insulated wire, wound in a rectangular groove.

In this, if desired, another coil (figs. 149, 150, next page) can be suspended at A when it is required to examine the action of two currents on each other; or, the suspended coil being removed, a galvanometer or helix can be placed within the fixed coil for purposes of comparison.

Fig. 151 shows the bifilar suspension.

"The equality of the tension of the suspension wires is ensured by their being attached to the extremities of a silk thread which passes over a wheel, and their distance is regulated by two guide-

wheels which can be set at the proper distance. The suspended

Elevation, Fig. 149.

Plan, Fig. 150.

Fig. 151.

coil can be moved vertically by means of a screw acting on the

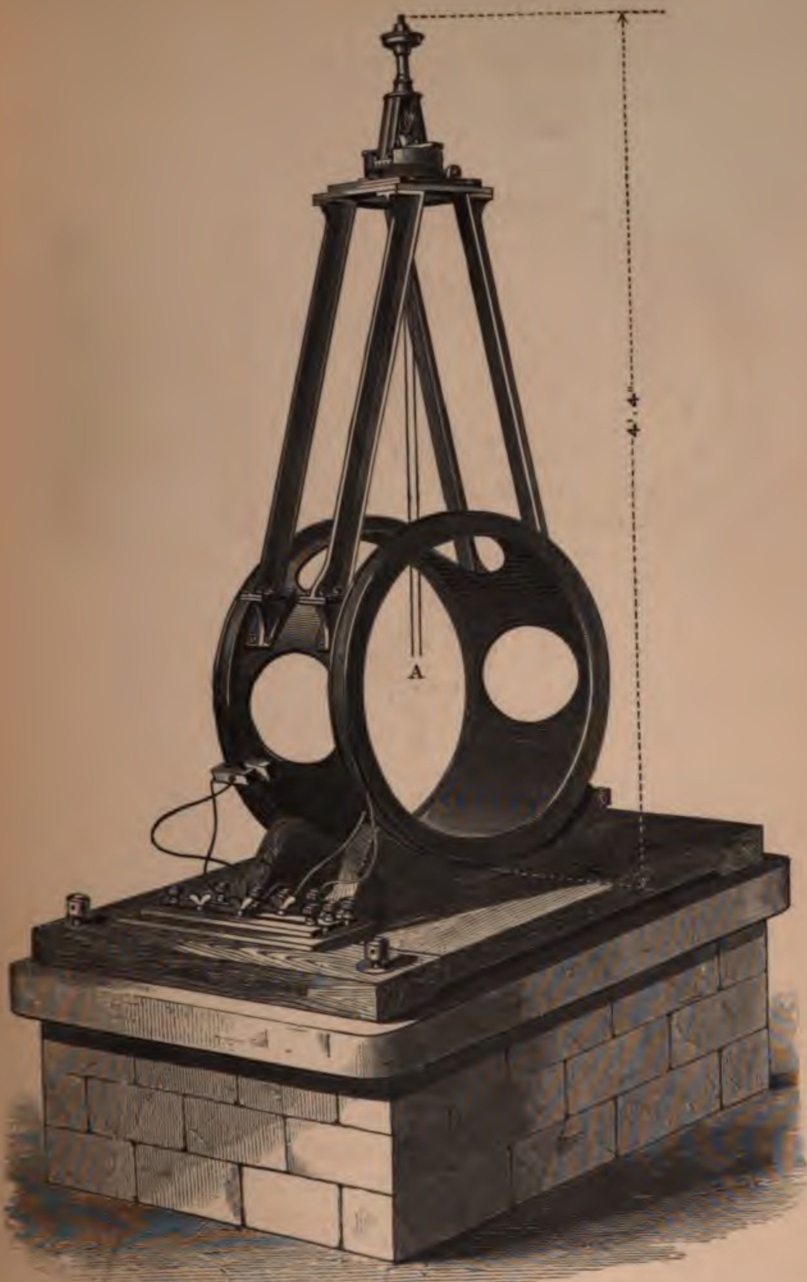


PLATE XXVII.—ELECTRO-DYNAMOMETER.

suspension-wheel, and horizontally in two directions by the sliding pieces shown at the bottom of fig. 151. It is adjusted in azimuth by means of the torsion screw, which turns the torsion-head round a vertical axis. The azimuth of the suspended coil is ascertained by observing the reflection of a scale, in the mirror shown just beneath the axis of the suspended coil."*

In fig. 150 the suspending wires are not shown. They pass up through the V's, and are held into them by the little springs, . Their distance apart can be set to any required whole number of millims. by means of the scales and arrows.

The distance apart of the upper ends of the suspending wires can be exactly regulated by verniers (not shown) engraved on the sliding pieces carrying the guide pulleys in fig. 151.

The torsion of a bifilar suspension depends on the *product* of the top and bottom distances of the wires, and, therefore, to adjust it, it is only necessary to adjust one of those distances.

* Maxwell's "Electricity," vol. ii. p. 331.

APPENDIX TO CHAPTER XXX.

To determine the Constants of a Helix.
Number of Windings.

In experiments on the magnetic effects of currents, it is sometimes necessary to use a large helix of wire in order to obtain a greater effect.

The action of a helix on a rod passing through it depends on the number of windings, and on the strength of the current.

In order to calculate the effect of any current, it is necessary to know the number of windings.

As the number of windings in a helix of more than one layer cannot be counted except at the time of winding, it is important to be able to determine it electrically, so as to save the expense of having a helix specially wound.

This can be done by comparing it with the great dynamometer, the number of whose windings is known.

Specimen Experiments.

The following are the details of a determination made in 1877, by the present writer,* of the number of windings in one of the helices of the electro-magnet shown in fig. 153, vol. ii. page 13.

Determination of the Number of Windings.

We must first determine the difference of magnetic potential at the two ends of the helix when a unit current passes through it. It is a quantity which we call N, and is a function of the number of windings and their arrangement; for if we know the magnetic intensity at each point of the axis of the helix due to a unit current, viz., what force is exerted by a unit current in a helix on a unit magnetic pole at that point, then we know how much work would have to be done to move this unit pole from one end of the helix to the other when a unit current was passing in it.

But if a, b be the ends and u_x the force at any point, then the above amount of work would be equal to

$$\int_a^b u_x dx = V_b - V_a \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where V is the potential at any point.

* Phil. Trans., 1877, page 4.

But the dimensions of magnetic potential are, in the electro-magnetic system,

$$[L^{\frac{1}{2}}M^{\frac{1}{2}}T^{-1}];$$

and these are also the dimensions of the strength of an electric current.

$\therefore$ N, which is the ratio of the former of these things to the latter, *is a number.*

The value of N for the helix was determined in the Cavendish Laboratory, Cambridge, by comparison with the great dynamometer of the British Association, Plate XXVII. vol. ii. page 3.

The intensities of the magnetic action were compared at 7 equidistant points in the axis of the helix, and the total force was obtained by integrating by Weddle's formula (Boole's "Finite Differences," p. 47), viz.,

$$\int_0^{6h} u_x\,dx = \tfrac{3}{10}\,h\,\{u_0 + u_2 + u_4 + u_6 + 5\,(u_1 + u_5) + 6u_3\},^* \quad . \quad . \quad . \quad (2)$$

where h is the distance between any two of the points, and u_x is the magnetic intensity at any point in terms of that of the dynamometer.

The mechanical arrangements were as follows:—the dynamometer was placed so that the plane of the coils was accurately vertical and in the magnetic meridian.

The axial line of the coils was then carefully found and marked by means of plumb-lines and cross-threads fixed to the table.

A strong T-shaped board supported on three levelling-screws was placed so that the part corresponding to the stem of the T passed through the coils in a horizontal plane parallel to their axis; on this the helix was laid and its axis brought into exact coincidence with that of the coils.

A boxwood cylinder about 20 centims. long was turned to fit nicely into the helix; a long thick brass wire terminating in a handle was fixed into one end, and a brass pin about 5 centims. long was fixed near one edge of the other.

To the end of the latter a magnet and mirror weighing only about a grain was hung by a silk fibre, so that when the pin was at the highest point the magnet hung in the axis of the cylinder. The helix being placed coaxial with the coils was pushed endways so that the centre point of the coils was just outside one end of it.

The cylinder was then inserted and adjusted, by means of cross-wires, so that the mirror hung exactly at the centre point, and a mark was then made on the handle corresponding to a mark on the stand of the instrument.

---

* Objections have been taken to the use of this formula, which gives, it is observed, much more weight to u_1 and u_5 than to u_2 and u_4, and does not furnish any approximation of a legitimate analytical character. While fully acknowledging the force of these objections, I have not thought it worth while to make any alteration, for this reason: the experiments, being made with resistance-coils, are susceptible of such close accuracy that the errors of any particular determination, even when multiplied by 5, cannot perceptibly affect the value of N deduced.

by reference to which the magnet could always be brought to the same position.

Thus while the helix was slid along the axis, the magnet inside it could always be placed at the centre point of the dynamometer. The distance between the inside ends of the helix was divided into six equal parts by means of seven pins stuck as sights into a slip of wood fixed along the top edge. Thus by sliding the helix along, till any one of the sights was between the vertical threads placed midway between the coils, the force at that point due to the helix could be compared with that due to the dynamometer by means of the needle at the centre.

The comparison was made by sending currents of different intensities through the helix and coils in opposite directions, and varying them till there was no action on the needle.

This was effected by dividing a current and passing one portion through the coils and the other through the helix, and interposing different resistances in each branch.

The annexed diagram (fig. 152) shows the connections.

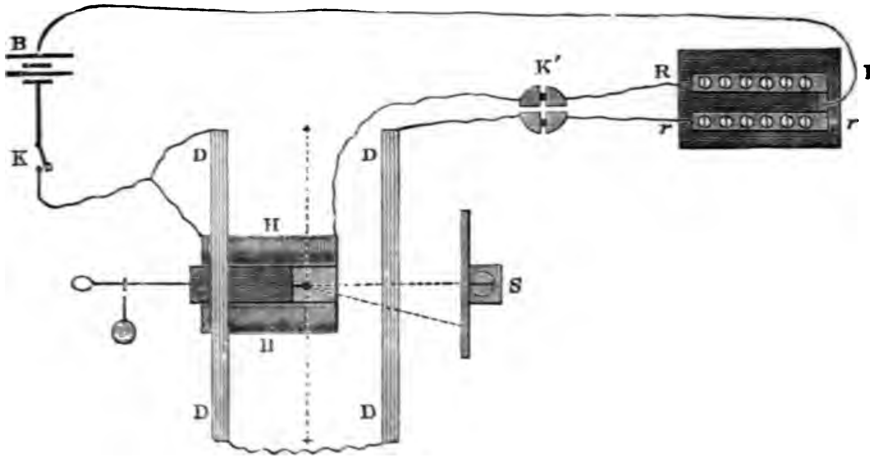


Fig. 152.

B is the battery, R and r the resistance coils.
D, the dynamometer coils. } And let these letters also represent
H, the helix. } their resistances.
● the magnet and mirror, whose angular position is observed by
S, the scale and lamp.
K K' are contact-keys.

Now when the actions on the needle are equal, the "powers" of the coils—that is, the forces they would respectively exercise with unit current—are inversely as the currents in them—that is, directly as the resistances $r + D$ and $R + H$.

The observations being repeated at each of the seven points, we have the intensity of the magnetic action of the helix at each of those points in terms of that of the dynamometer.

Thus if P be the "power" of the dynamometer with unit current, and u_x the "power" of the helix at a point x with the same current, then the difference of magnetic potentials at the ends of the helix is for unit current

$$N = \int_0^{6h} u_x \, dx = \frac{3h}{10} P \left\{ \frac{H + R_0}{D + r_0} + \frac{H + R_{2h}}{D + r_{2h}} + \frac{H + R_{4h}}{D + r_{4h}} + \frac{H + R_{6h}}{D + r_{6h}} \right.$$

$$\left. + 5 \left(\frac{H + R_h}{D + r_h} + \frac{H + R_{5h}}{D + r_{5h}} \right) + 6 \frac{H + R_{3h}}{D + r_{3h}} \right\} \quad . \ . \ . \ . \quad (3)$$

where h is $\frac{1}{6}$ the length of the helix.

In the helix used, the following results were obtained :—

$$h = 4{\cdot}39 \text{ centims.}, \begin{cases} H = \ 1{\cdot}01, \text{ take} = 1{\cdot}00, \\ D = 28{\cdot}15 \quad \text{,,} \quad 28{\cdot}1. \end{cases}$$

Mean values of u_x with different values of r.—

r.	u_0.	u_1.	u_2.	u_3.	u_4.	u_5.	u_6.
$r = 100$	2·724 P*	4·973 P	5·667 P	5 777 P	5·574 P	4·808 P	2·724 P
$r = 200$	2·762 P	4·976 P	5 659 P	5·725 P	5 572 P	4·814 P	2 722 P
$r = 1000$	2 722 P	4 962 P	5·681 P	5·798 P	5·592 P	4·639 P	2·723 P
Mean ..	2·736 P	4·970 P	5·669 P	5·766 P	5·579 P	4·754 P	2·723 P

Specimen observation.

$$r = 100, \ u_3 = P \frac{739 + H}{100 + D} = 5 \ 777 \ P$$

Hence

$$N = \int_0^{6h} u_x \, dx = \tfrac{3}{10} 4{\cdot}39 \text{ centims. } \{16{\cdot}707 + 48{\cdot}620 + 34{\cdot}596\} P$$

$$= 131{\cdot}732 \text{ P.}$$

Now $\qquad P = 81{\cdot}1620,$

$\qquad \therefore \ 131{\cdot}732 \ P = 10751{\cdot}96.$

Now the value of N for any helix with unit current taken with respect to the whole length of its axis produced to an infinite length in both directions is, by Art. 676 of Professor Clerk Maxwell's "Electricity," $4\pi n$, where n is the number of windings.

When the length l is finite compared with the radius a. the value of N for that part of the axis which is included between the ends is

$$N = 4 \pi n \frac{\sqrt{l^2 + a^2} - a}{l} \quad . \ . \ . \ . \ . \quad (5)$$

(see Clerk Maxwell's "Electricity," Art. 676).

* P is the "power" of the dynamometer.

Now if we calculate $n = \frac{N}{4\pi} \frac{l}{\sqrt{l^2 + a^2} - a}$, taking a the mean radius, this will give the number of windings in the helix.

Now as $a = 4{\cdot}84$ centims., and $N = 10752$, we have

$$n = \frac{10752}{4\pi} \cdot \frac{26{\cdot}34}{\{26{\cdot}34^2 + 4{\cdot}84^2\}^{\frac{1}{2}} - 4{\cdot}84};$$

$$\therefore \log n = \log 10752 + \log 26{\cdot}34 - \log 4\pi - \log \overline{(l^2 + a^2)^{\frac{1}{2}} - a}$$

$$\{\text{last term} = \log 21{\cdot}92\}$$

$$= 4{\cdot}0314893 + 1{\cdot}4206158 - 1{\cdot}0991971 - 1{\cdot}3408405$$

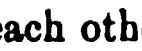
$$= 3{\cdot}0120680,$$

$$\therefore n = 1028{\cdot}15,$$

$\therefore$ there are 1028 windings on the helix.

Verification.

Now in the length of the helix there are 91 windings on the outside layer, and the ratio of the length to the difference of the internal and external radii is $\frac{26{\cdot}34}{3{\cdot}47} = 7{\cdot}5$ about.

$\therefore$ assuming that the number of layers per centim. of radius is the same as the number of windings per centim. of length (it would really be a little greater, as they fit into each other, ), we have

$$n = \left\{91 \times \frac{91}{7{\cdot}5}\right\} = 1092,$$

which is sufficiently near the calculated result, viz. $n = 1028$, to show that no large mistake has been made, as, for instance, writing down a log, with a wrong index.

Closer agreement could hardly be expected, as the helix was made for a different purpose, and no particular pains were taken to wind it uniformly. It is also probable that the instrument-maker took more pains to wind the wires of the outside layer, which could be seen, close together than those of the inside ones, which were hidden.

Sum of Areas.

In order to measure the magnetic effect of a given current at any point *outside* the helix, it is necessary to know the sum of the areas of all the windings of the helix.

Let us call this quantity $\Sigma(A)$ for the helix, and $\Sigma(A)'$ for the dynamometer.

$\Sigma(A)'$ is known by measurement, and is equal to 870200 sq. centims.

To determine $\Sigma(A)$ the helix and dynamometer were placed exactly concentric. A magnet and mirror was suspended rather more than a metre distant from them, first in front and then behind, so as to correct any error in centering; and varying currents, C, C′, were sent opposite ways till there was no deflection.

At this distance the helix and the dynamometer could each be considered to be replaced by their equivalent magnetic discs, and the difference between

r and r_1, the respective distances from the centres of their ends to the magnet, may be neglected in comparison with those quantities themselves.

The formula for $\Sigma(A)$ then becomes

$$\Sigma(A) = \frac{C'}{C} \Sigma(A)'.$$

Where there was no action on the suspended magnet, it was found that

$$\frac{C}{C'} = 11{\cdot}23,$$

which gives $\Sigma(A) = 77488{\cdot}8$ sq. centims.*

Another determination, with a different dynamometer, gave $\Sigma(A) = 77417.2$ sq. centims.†

CALCULATION OF THE STRENGTH C OF A CURRENT IN THE HELIX IN TERMS OF THE DEFLECTION δ OF THE SUSPENDED MAGNET.

When the sum of the areas is known, the helix will act as its own galvanometer—that is, the strength of a current in it can be calculated from the deflection of a magnet outside it.

The helix must be placed magnetic East and West, and the magnet suspended so that it hangs in the plane passing through the centre of the helix.‡

It can then be shown mathematically that if r be the distance from the magnet to the centre of one end of the helix, $2l$, the length of the suspended magnet, m the strength of its pole, and H the horizontal component of the earth's magnetism, we shall have

$$Hml \tan\delta = \Sigma(A) \frac{ml}{r^3} C$$

or

$$H \tan\delta = \frac{C\Sigma(A)}{r^3},$$

which gives

$$C = \frac{Hr^3}{\Sigma(A)} \tan\delta \quad . \quad . \quad . \quad . \quad . \quad (6).$$

---

* This measurement was made by Prof. Clerk Maxwell.

† This measurement was made by the Author.

‡ Phil. Trans., 1877, pages 12 and 16.

CHAPTER XXXI.

ELECTRO-MAGNETS—DIAMAGNETISM AND MAGNE-CRYSTALLIC ACTION.

If an insulated wire be wound round a bar of iron or steel, and an electric current be sent round the wire, the core becomes a magnet with its marked end in the position in which the marked end of a permanent magnet would come to rest, if it were placed, free to turn, inside the helix instead of the iron core. When the core is of soft iron it becomes magnetized on the passage of the current, and loses its magnetism when the current ceases. When the bar is of steel, it resists the assumption of the magnetic state, but, when magnetized, retains its magnetism for an indefinite time after the cessation of the current.

The property of soft iron is taken advantage of in the construction of "electro-magnets," by means of which far greater magnetic forces than are given by any steel magnets are obtained, with the additional advantage that they are under perfect control, for within certain limits the strength of the temporary iron-magnet is proportional to the strength of the current in the wire.

Electro-magnets are frequently made in the horse-shoe form, and when in this shape usually consist of two parallel pillars of soft iron, connected at one end by a massive cross-bar of the same metal. The wires are wound on hollow brass reels, which can be lifted on and off the iron pillars.

A magnet in the possession of the author consists of a "horse-shoe," fig 153, whose pillars are each 13 inches long and 2½ inches diameter; the helices, which are 12 inches long and 5 inches external diameter, each contain about 1000 turns of insulated copper wire of about No. 18 gauge. The helices weigh about 35 lbs. each. Such a magnet, if fixed with its poles down-

ward, and excited by a powerful current, would probably carry a weight of from one to three tons attached to the armature. Magnets of this size, however, are used for a different purpose. Their magnetic action is so intense that it affects almost all known

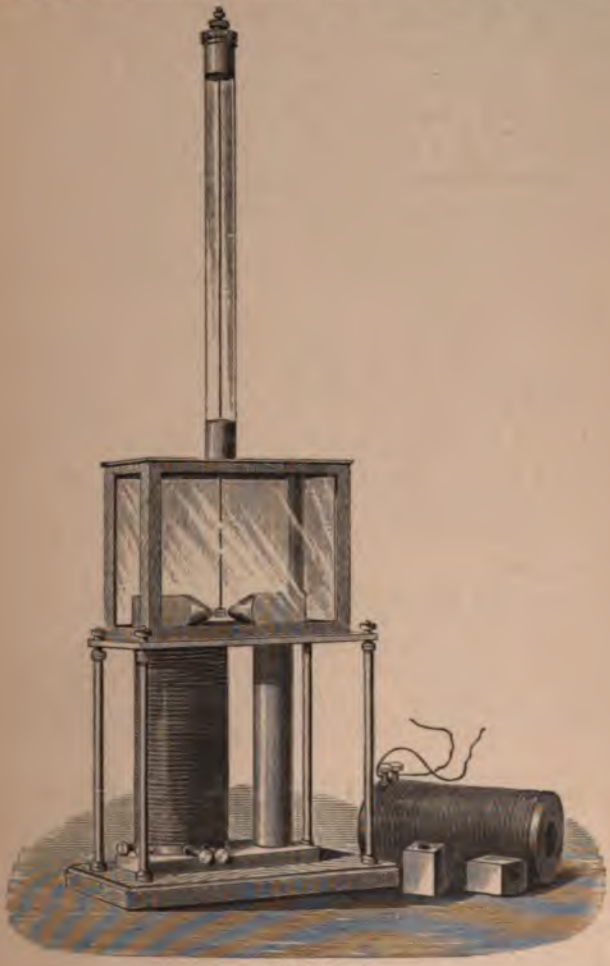


Fig. 153.

substances, in addition to those few commonly known as magnetic. The action on most substances is too feeble for the attraction or repulsion to be observed directly.

To observe the action, say, on a piece of glass, the magnet is placed with its pillars vertical and the cross bar at the bottom.

The free poles then project up about an inch above the helices. Two blocks of soft iron, which are called the movable poles, are placed upon the tops of the pillars. A body placed between these blocks is practically between two horizontal poles.

By sliding the blocks, the horizontal poles can be either approached close to each other or separated to a distance of some five inches. One end of each block is flat, so as to give the pole a vertical plane face about two inches square; the other ends are tapered to a blunt point. Either the flat or pointed ends can be turned towards each other. A body placed between the two pointed poles is subjected to more intense forces, while one placed between the flat poles is in a more uniform field of force; the action of the points being to concentrate the magnetic action in one place.

In order to measure the magnetic actions of those bodies which are very feebly affected by the magnet, the torsion balance is used, being a modification of the Colomb's Balance described in Part I.* A homogeneous body being suspended between the poles by the torsion fibre will, if it is attracted, take up its position with its longest diameter pointing from pole to pole; and if it is repelled, its longest diameter pointing across the line joining the poles.

Definition.—The line joining the poles is called the axial line; the line at right angles to it, the equatorial.

The amount of the attraction or repulsion can be measured by the number of degrees of torsion required to displace the suspended body a given number of degrees from its position of rest.

Definition.—Iron and similar bodies which are attracted by the magnet are called Ferro-magnetic, or sometimes Paramagnetic bodies. Substances which are repelled are called Diamagnetic.

The type of diamagnetic bodies is bismuth, which is repelled from a powerful magnet with considerable force. A small sphere ¼ inch in diameter hung by a thread, say, two feet long, between the pointed poles of a powerful magnet, may be repelled so as to move it as much as a quarter of an inch out of the vertical.

The phenomena of diamagnetism were first observed by

* Vol. i. p. 33.

Faraday,* on a piece of the heavy glass which he had previously used for the experiments on the rotation of the plane of polarization, which will be described in Part IV. of this book. The paper containing the account of the discovery of diamagnetism was read before the Royal Society, Dec. 18, 1845, and will be found in the *Phil. Trans.* 1846, and in the *Experimental Researches* (2243).

In these first experiments a rod of heavy glass was suspended between the poles of the great horse-shoe magnet of the Royal Institution. It was found that the bar always placed itself equatorially, that is, at right angles to the line joining the poles, and that it was in stable equilibrium in that position. There was also another position of rest when the length of the bar was exactly axial; but in this case the equilibrium was unstable, and on the least displacement the bar moved to the equatorial position.

No difference could be detected between the ends of the bar; the direction in which either end pointed when in stable equilibrium depended solely on the direction in which it was displaced from the position of unstable equilibrium, thus showing that no permanent polarity, analogous to the polarity of a steel magnet, is acquired by the glass.

Faraday continued his experiments on a great number of substances, among which phosphorus showed the effect "as powerfully as heavy glass, if not more so." He also experimented on a great number of liquids. The liquids were contained in a very thin glass tube, of the shape shown in fig. 154.

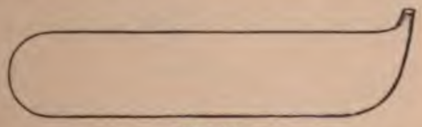


Fig. 154.

The action of the glass tube itself had of course to be allowed for, but, by making the tube of very thin flint glass, its action could be made very small, and, by alternate experiments with it

* "Isolated observations by Brugmans, Becquerel, Le Baillif, Saigy, and Leebeck had indicated the existence of a repulsive force exercised by the magnet on two or three substances, but these observations which were unknown to Faraday had been permitted to remain without extension or examination." Tyndall, "Faraday as a Discoverer," p. 110.

full and empty, the proper action of the liquid could be easily determined. The shape of the tube obviated the necessity of closing it—an important consideration, as cork, sealing-wax, and other substances are generally magnetic unless special care has been taken to prepare them free from iron.

The following is a list of substances which Faraday found to be diamagnetic :—

Rock crystal.
Sulphate of lime.
Sulphate of baryta.
Sulphate of soda.
Sulphate of potassa.
Sulphate of magnesia.
Alum.
Muriate of ammonia.
Chloride of lead.
Chloride of sodium.
Nitrate of potassa.
Nitrate of lead.
Carbonate of soda.
Iceland spar.
Acetate of lead.
Tartrate of potash and antimony.
Tartrate of potash and soda.
Tartaric acid.
Citric acid.
Olive oil.
Oil of turpentine.
Jet.
Caoutchouc.
Sugar.
Starch.
Gum arabic.
Wood.
Ivory.
Water.
Alcohol.
Ether.
Nitric acid.
Sulphuric acid.
Muriatic acid.
Solutions of various alkaline and earthy salts.
Glass.
Litharge.
White arsenic.
Iodine.
Phosphorous.
Sulphur.
Resin.
Spermaceti.
Caffeine.
Cinchona.
Margaric acid.
Wax from shellac.
Sealing wax.
Mutton, dried.
Beef, fresh.
Beef, dried.
Blood, fresh.
Blood, dried.
Leather.
Apple.
Bread.

Among metals Faraday found—

Antimony,
Bismuth,
Cadmium,
Copper,
Gold,
Lead,
Mercury,
Silver,
Tin,
Zinc,

to be diamagnetic.

Iron, nickel, and cobalt were certainly paramagnetic, while platinum, palladium, and titanium showed paramagnetic effects,

but so feebly that he could not be certain whether they were not due to the accidental presence of iron, nickel, or cobalt.

Generally speaking, the distinction between para- and diamagnetic substances is this:—Paramagnetics tend to move from weak to strong places of force, while diamagnetics tend to go from strong to weak places. Faraday found that almost all compounds of paramagnetic metals were themselves paramagnetic. Blood and yellow ferro-cyanide of potassium are, however, exceptions, as they both contain iron and are diamagnetic.

From some later experiments he deduced the following list, at one end of which is iron, the strongest paramagnetic; at the other, bismuth, the strongest diamagnetic. Metals nearest the neutral point 0 have the least action either way:—

Magnetic.	*Diamagnetic.*
Iron.	Bismuth.
Nickel.	Antimony.
Cobalt.	Zinc.
Manganese.	Cadmium.
Chromium.	Sodium.
Cerium.	Mercury.
Titanium.	Lead.
Palladium.	Silver.
Platinum.	Copper.
Osmium.	Gold.
	Arsenic.
	Uranium.
	Rhodium.
	Iridium.
	Tungsten.

0

It must be remembered that the diamagnetism of bismuth is very much smaller than the magnetism of iron.

The strength of the pole of an electro-magnet having an iron core may be as much as from 32 to 45 times the magnetizing force, while with a bismuth core it would only be about

$$-\frac{1}{400,000} \text{ of it.}$$

Diamagnetic Polarity.

As soon as the facts of diamagnetism were established, the question arose—Are the effects observed due to simple repulsion,

or is there a true diamagnetic polarity induced?—that is, Do diamagnetic bodies, when under the influence of magnetic forces, become temporary magnets, in the same manner as pieces of soft iron under the same circumstances, only with their poles in the opposite directions?

While the marked pole of the magnet induces, in a piece of soft iron in its neighbourhood, an unmarked pole at the side nearest to it and a marked pole at the farther side, we should, on the hypothesis of diamagnetic polarity, have, if a piece of heavy glass were substituted for the soft iron, a marked pole at the side of the heavy glass nearest to the marked pole of the inducing magnet, and an unmarked pole at the further side. Faraday made many attempts to determine whether or not diamagnetic polarity exists.* His method consisted in placing at one end of an electro-magnet an extra helix not connected to the battery, but connected to a sensitive galvanometer. In this helix he placed bars of bismuth and other diamagnetic substances, with their ends close to the end of the core of the electro-magnet. If the bismuth bar had been thrown into a polar state, it should, on being moved suddenly away from the magnet, while the magnet was excited, have induced a current in the helix surrounding it, and, on being moved back, a current in the opposite direction. Faraday connected the bismuth bars to a crank worked by a fly-wheel, by which they could be moved rapidly backward or forward, while a commutator, driven by the same machinery, sent all the currents in the same direction through the galvanometer.

He was, however, unable to obtain any evidence whatever in favour of diamagnetic polarity. His apparatus does not seem to have been of extreme sensitiveness. In particular, the almost impossibility of making the reversals of the current by the commutator exactly synchronize with the reversals of the motions of the bismuth cylinder, must have considerably obscured any effect which was produced. A commutator was rendered necessary owing to the fact that an apparatus with suspended coil, like a small dynamometer now used for measuring alternating currents, was not then invented. His galvanometer also, though a very sensitive astatic one, could not be compared for delicacy to the reflecting instruments since invented. The results

* "Experimental Researches," 2640.

obtained by Faraday with crystals of protosulphate of iron, when compared with the results given by the same substance in the experiments of Professor Tyndall (which we are about to describe), show that the apparatus used by the latter was about one hundred times as sensitive as that used by Faraday. Matteucci also worked at the subject, but without decisive results.

In 1851 M. Verdet published* some experiments which caused him to decide against the hypothesis of diamagnetic polarity. His method of experimenting was as follows:—

Helices similar to those of an electro-magnet were placed upon the arms of a large permanent steel magnet of horse-shoe form. In front of the poles of the steel magnet a bar of the diamagnetic substance was caused to revolve rapidly round an axis perpendicular to its length, by means of a multiplying wheel. No battery was used, but the ends of the helices were connected to a delicate galvanometer at a sufficient distance from the magnet to be free from its direct influence. When a bar of iron was substituted for the diamagnetic substance, the steel magnet induced in it a magnetic polarity which constantly changed as the bar revolved, causing it to become a varying magnet which re-acted on the steel magnet, and caused temporary changes in its magnetization; which changes induced currents in the helices, whose effects were observed on the galvanometer.

In a second series of experiments the steel magnet was replaced by a soft iron electro-magnet (excited by a battery), whose helix, consisting only of a few layers, was inside the helix which was connected with the galvanometer.

M. Verdet expected that, if diamagnetic polarity existed, the substitution of a bismuth bar for an iron one would reverse the direction of the galvanometer deflection. No such effect was observed, and its absence caused him to decide against the existence of diamagnetic polarity.

The reason why he obtained no reverse effect is sufficiently obvious. All his diamagnetics were conductors of electricity; whether they became polar or not, electric currents would be induced in them which would re-act directly upon the helices. These indûced currents would be entirely independent of the magnetic polarity of the bodies, and would be so great as to

* "Ann. de Chimie," III. Ser., tome xxxi. p. 187. "Œuvres de Verdet." tome i. p. 43.

entirely mask any effect which could be expected from true diamagnetic induction.

In 1855 Professor Tyndall* published an account of a series of experiments, by means of which he obtained an entirely independent proof of the polarity of bismuth.

The bismuth bar, ll' (fig. 155), was suspended inside a fixed

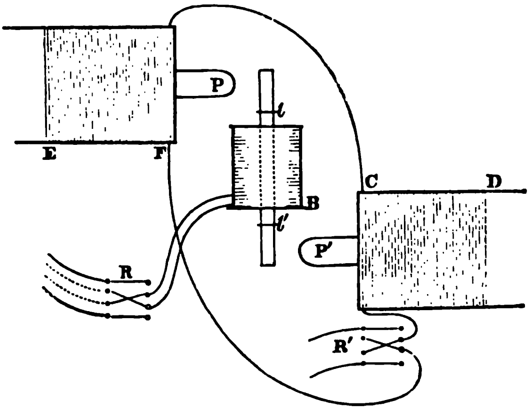


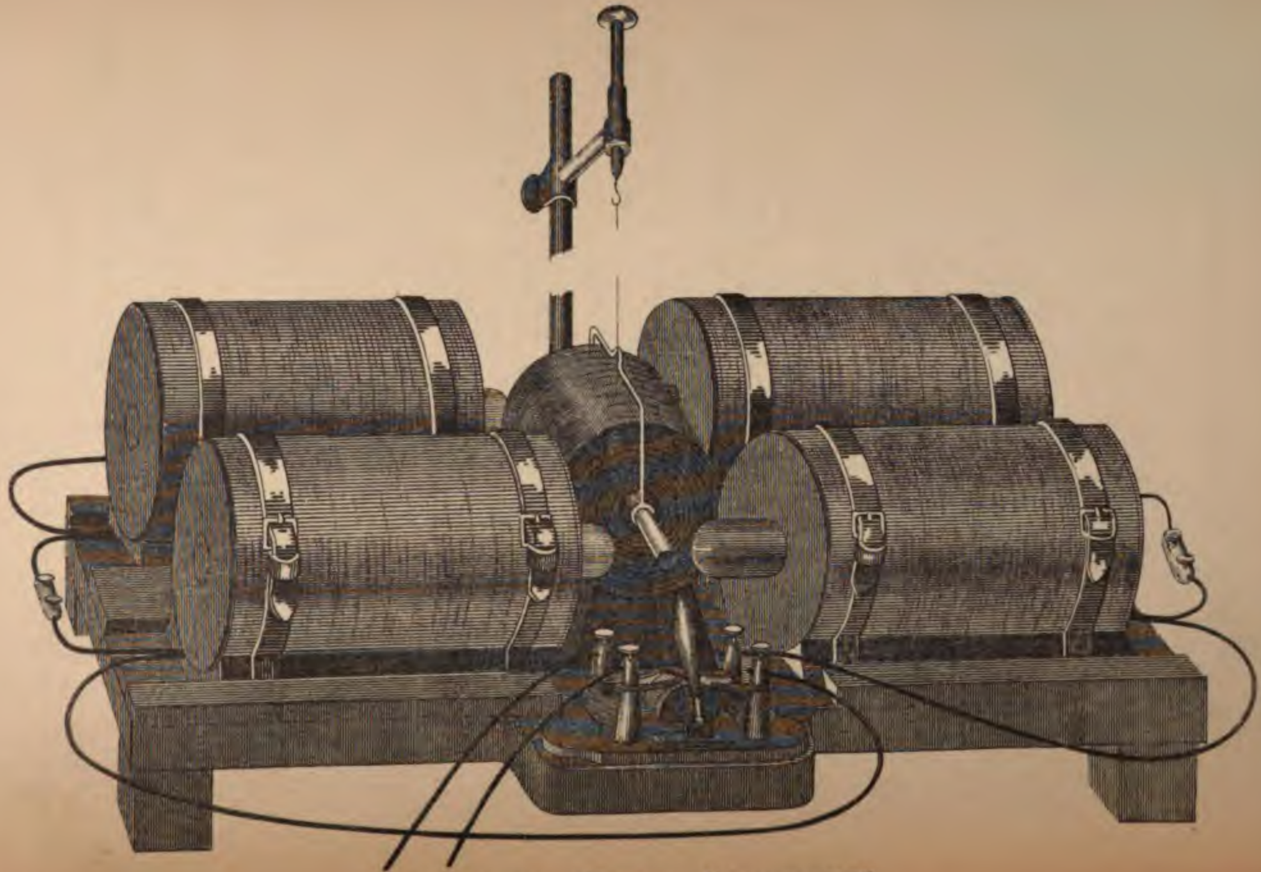
Fig. 155.

helix, B, the tube of which was considerably larger than the bar; so that, within certain limits, the bar could swing like a galvanometer needle. Two single electro-magnets P P′ were placed in the position shown. We know that if a bar of iron were substituted for the bismuth bar, it would be magnetized by the current in the helix, A B, and deflected to the right or left by the poles, P P′, according to the directions of the currents in the helix and the magnet. When the current in A B was such that the polarity of the ends of the iron bar ll', was the same as the polarity of the poles P P′ opposite to them respectively, the bar was repelled; when the current in the helix was reversed, the bar was attracted.

On substituting a bar of bismuth for the bar of iron, exactly analogous effects were produced; but the directions of the currents which had produced attraction with the iron bar now produced repulsion with the bismuth and *vice versâ*, showing that the current in the helix, which produced a particular polarity in the iron bar, produced a ***reversed polarity*** in the bismuth. The

* Tyndall, "Diamagnetism and Magne-Crystallic Action," p. 130 (Longmans, Green, & Co., 1870); and Phil. Trans. 1855, p. 33.

Plate XXVIII.



Tyndall's Electro-Diamagnet

commutators, R R′, allowed every possible combinations of currents to be tried.

Plate XXVIII. is a drawing of a much larger apparatus devised by Professor Tyndall, for showing the same effect on a large scale, suitable to class experiments. Four electro-magnets were used, forming two horse-shoe magnets; and the currents were arranged so that each end of the suspended bar was at the same time attracted by the pole on one side of it and repelled by that on the other. In the picture, the commutator for the magnets is seen in front, but that for the helix is out of sight at the back of the instrument.

By the use of this apparatus Professor Tyndall was able to cause deflections of a bismuth cylinder 14 in. long and 1 in. diameter, which were sufficiently distinct to be visible to a large audience.

In 1852, Professor Weber published a memoir,* in which he discussed some of the mathematical consequences of diamagnetic polarity. He pointed out that—

"*The magnetism of two iron particles lying in the line of magnetization is increased by their mutual action, but, on the contrary, the diamagnetism of two bismuth particles lying in this direction is diminished by their mutual action.*

"The reverse occurs in both cases if the particles lie in a line perpendicular to the line of magnetization.

"From this it follows that to impart by a given magnetizing force the strongest possible magnetism to a given mass of iron, we must convert it into a bar as long and thin as possible, and set its length parallel to the line of magnetizing force, and that to impart the maximum diamagnetism to a given mass of bismuth, we must convert it into the thinnest plate possible, and set its thickness parallel to the line of magnetizing force."

Professor Weber then went on to describe some experiments on diamagnetic polarity, by means of which he obtained a proof of its existence by a method totally different to that employed by Professor Tyndall.

In 1856, Professor Tyndall described a series of experiments made by him with Weber's method, and with an apparatus devised for him by the latter. As the principle of these experi-

* Taylor's "Scientific Memoirs" (Nat. Phil.), 1853, p. 163; or Pogg. Ann. LXXXVII., p. 145.

ments is the same as that of Weber's, and as there were many improvements in detail introduced by Professor Weber and Professor Tyndall in the new investigation, we shall only describe the latter.

The following is Professor Tyndall's* account of it:—

"A sketch of the instrument employed is given in fig. 156. B O, B′ O′ is the outline of a rectangular box, the front of which is removed so as to show the apparatus within. The back of the box is prolonged, and terminates in two semi-circular projections, which have apertures at H and H′. Stout bolts of brass, which have been made fast in solid masonry, pass through these apertures, and the instrument being secured to the bolts by screws and washers, is supported in a vertical position, being free from all disturbance save such as affects the foundations of the Royal Institution. All the arrangements presented to the eye in fig. 156 are made fast to the back of the box, but are unconnected with the front, so as to permit of the removal of the latter. W W′ are two boxwood wheels with grooved peripheries which permit of motion being transferred from one wheel to the other by means of a string *s s′*. Attached to this string are two cylinders, *m n*, *o p*, of the body to be examined; in some cases the cylinders are perforated longitudinally, the string passes through the perforation, and the cylinders are supported by knots on the string. H E, H′ E′, are two helices, of copper wire overspun with silk and wound round two brass reels, the upper ends of which protrude from H to G, and from H′ to G′. The internal diameter of each helix is 0·8 of an inch, and its external diameter about 1·3 inch; the length from H to E is 19 inches, and the centres of the helices are 4 inches apart; the diameters of the wheels W W′ being also 4 inches. The cross bar G G′ is of brass, and through its centre passes the screw R. From this screw

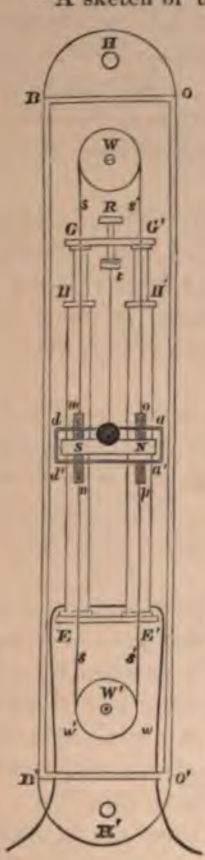


Fig. 156.

* Tyndall's "Diamagnetism," p. 158.

depend a number of silk fibres which support an astatic arrangement of two magnets, the front one of which, S N, is shown in fig. 156. An enlarged section of the instrument through the astatic system is shown in plan in fig. 157; and the position of the helices is shown to be between the magnets. It will be seen that the astatic system is a horizontal one and not vertical, as in the ordinary galvanometer. The black circle in front of the magnet, S N, fig. 156, is a mirror, which is shown in section at M, fig. 157.

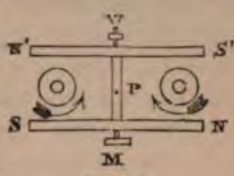


Fig. 157.

To balance the weight of this mirror and adjust the magnets in a horizontal position, a brass washer, W, is caused to move along a screw until a point is attained at which its weight brings both the magnets into the same horizontal plane. There is also another adjustment which permits of the magnets being brought closer together, or separated more widely asunder. The motions of this compound magnet are observed by means of a distant scale and telescope, according to the method applied to the magnetometer of Gauss.* The rectangle, *d a*, *d' a'*, fig. 156, is the section of a copper damper, which, owing to the electric currents induced in it by the motion of the magnet, soon brings the latter to rest, and thus expedites experiment.

"It is well known that one end of a magnet attracts, while the other repels the same pole of a magnetic needle; and that between both there is a neutral point which neither attracts nor repels. The same is the case with the helices, H E and H' E'; so that when a current is sent through them, if the astatic needle be exactly opposite the neutral point, it is unaffected by the helices. This is scarcely attainable in practice; a slight residual action remains which draws the magnets against the helices; but this is very easily neutralized by disposing an external portion so as to act upon the magnets in a direction opposed to that of the residual action. Here then we have a pair of spirals, which, when excited, do not act upon the magnets, and which therefore permit us to examine the pure action of any body capable of magnetic excitement and placed within them.

"In the experiments to be described, it was arranged that the current should always flow in opposite directions through the

* See vol. i. p. 169.

two spirals; so that if the cylinders within them were polar, the two upper ends of these cylinders should be poles of opposite names, and consequently the two lower ends opposed also.

"Suppose the two cylinders *m n*, *o p*, to occupy the central position indicated in fig. 156: then, even if the cylinders became polar through the action of the surrounding current, the astatic magnets, being opposite to the neutral points of the cylinders, would experience no action from the latter.

"But suppose the wheel W′ to be turned so that the two cylinders are brought into the position shown in fig. 158, the

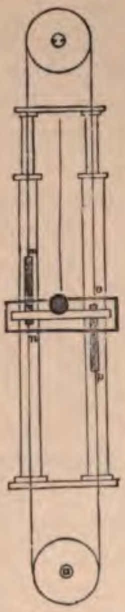


Fig. 158.

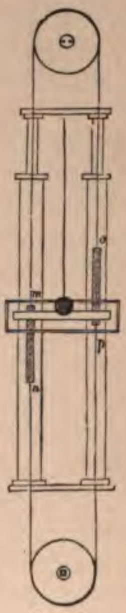


Fig. 159.

upper end *o* of *o p*, and the lower end *n* of *m n*, will act simultaneously on the suspended magnets. For the sake of illustration, let us suppose the ends *o* and *n* to be both north poles, and that the section, fig. 157, is taken when the bars are in the position shown in fig. 158. The right-hand pole *o* will attract S′ and repel N, which attraction and repulsion sum themselves together to produce a deflection of the system of magnets. On the other hand, the left-hand pole *n*, being also north, will attract S, and repel N′, which two effects also sum themselves to produce a deflection in the same direction as the former two.

Hence, not only is the action of terrestrial magnetism annulled by this arrangement, but the moving force due to the reciprocal action of the magnets and the bodies within the helices, is increased fourfold. By turning the wheel in the other direction, we bring the cylinders into the position shown in fig. 159, and thus may study the action of the ends *m* and *p* upon the magnets.

"The screw R, fig. 156, is employed to raise or lower the magnets. At the end, *t*, of the screw, is a small torsion circle which can be turned independently. By means of the latter the suspending fibre can be twisted or untwisted without altering the level of the magnets.

"The front is attached to the box by brass hasps, and opposite to the mirror M a small plate of glass is introduced, through which the mirror is observed; the magnets within the box being thus effectually protected from the disturbances of the external air. A small handle to turn W′ accompanied the instrument from its maker; but in the experiments, I used instead of it a key attached to the end of a rod 10 feet long; with this rod in my right hand and the telescope and scale before me, the experiments were completely under my own control. Finally, the course of the current through the helices was as follows:—

"Proceeding from the platinum pole of the battery it entered the box along the wire *w*, fig. 156, which passed through the bottom of the latter; thence through the helix to H′, returning to E′; thence to the second helix returning to E, from which it passed along the wire *w*′ to the zinc pole of the battery.

"A commutator was introduced in the circuit, so that the direction of the current could be reversed at pleasure."

We see that this method of experimenting has the great advantage, that in it a permanent deflection is always observed, and thus the effect of induction currents is entirely eliminated. We quote a few of Professor Tyndall's numbers, in order that the decisive character of the experiments may be fully appreciated. The positions 1, 2, 3 are the positions of the cylinders shown in figs. 158, 156, 159, respectively.

Bismuth cylinders, length 3 inches, diameter, 0·7.

	Position 1.	Position 2.	Position 3.
Scale readings .	468	482	493

This set of experiments was repeated many times with a perfectly uniform result. On reversing the battery current, the

scale readings varied in the opposite direction, showing that the "polarity of the bismuth cylinders depends on the direction of the current, changing as the latter changes. It was invariably found, that with the same position of cylinders and direction of current, the deflection produced was in opposite directions for para- and dia-magnetic bodies."

In order, however, to completely answer the objections founded on the supposition that the effects observed are due to currents induced in the cylinders, Professor Tyndall repeated his experiments, using cylinders which were not conductors of electricity. The following numbers were obtained with rods of heavy glass, length 3 inches, width 0·6, depth 0·5:—

	Position 1.	Position 2.	Position 3.
Scale readings .	664	662	660

In six different series of experiments made with this substance the same invariable result was obtained. The deflections were in all cases identical in direction with those produced by bismuth under the same circumstances. The other diamagnetic solids which were observed were antimony, calcareous spar, statuary marble, phosphorus, sulphur, nitre, and wax. They all gave perfectly distinct and unmistakable indications of diamagnetic polarity; cylinders of copper were also tested. This substance is an excellent conductor, but a very feeble diamagnetic. If the effects observed had been due to currents in the cylinders. the deflection produced by copper should have been about forty times as great as that produced by bismuth. On trying the experiment, however, the copper cylinders gave a deflection which was hardly perceptible; a fact—on the hypothesis of polarity—easily explained by their very feeble diamagnetic capacity.

Polarity of Diamagnetic Liquids.

Water, and bisulphide of carbon, enclosed in thin glass tubes, were both experimented on; and in each case distinct diamagnetic polarity was observed.

Final Experiments.

A corresponding series of experiments was made on paramagnetic solids and liquids. In every case the deflection produced was in opposite direction to that given by diamagnetic substances.

Among the paramagnetics examined were—slate of various kinds, chloride, sulphate and carbonate of iron in powder, ferro-prussiate of potash, and muriate of cobalt. In the case of chloride of iron the action was so powerful that the needle was forced against the helices.

Some final experiments were made on bismuth, which had been reduced to a state of fine powder and exposed to the air for some days, which had caused each particle to be covered with a coat of oxide. An experiment with a galvanometer showed that this powder was totally unable to conduct the current of even a powerful battery. On filling two glass tubes with the powder and placing them in the instrument, it was found they acted almost, if not quite, as powerfully as the solid bismuth cylinders.

MAGNE-CRYSTALLIC ACTION.

In all the experiments which we have hitherto described, we have considered the bismuth and other substances to be in a homogeneous state. When, however, they are in a heterogeneous or crystalline state, it was observed by Faraday that considerable differences are observed in their deportment under the action of powerful magnets.

The general law which determines the behaviour, in the magnetic field, of bodies whose density is not the same in all directions is, that *the magnetic axis induced in the body coincides with the line of greatest density*.

In crystals this line is parallel to the cleavage planes; that is, a diamagnetic crystal will set with its cleavage planes equatorial when suspended between the poles of a magnet, even when the diameter at right angles to the cleavage planes is considerably longer than that measured along them.

If, then, a bar of crystal, not too long, be cut so that its cleavage planes are perpendicular to the length of the bar, its behaviour, when suspended between the poles of a magnet, would be opposite to that of a homogeneous bar of the same shape, composed of a substance having the same magnetic properties.

The reason of this is that the magnetic induction parallel to the cleavage planes is so much stronger than that perpendicular to them, that the couple tending to set the cleavage planes equatorial (if the crystal be diamagnetic) is stronger than that

tending to set the length of the bar equatorial, in spite of the longer arm of the latter couple.

If, however, the length of the bar is very much greater than its breadth, the difference in the magnetic inductions in the two directions will not be able to compensate the difference in length of the arms of the couples. In this case the bar will set like a homogeneous substance, only it will require less force to displace it from its position of equilibrium.

The first observations "on the crystalline polarity of bismuth and other bodies" were made by Faraday. His paper on the subject formed the Bakerian Lecture for 1849, and will be found in the *Phil. Trans.* for that year.*

The subject was continued by Professor Tyndall, and his various papers on it are collected in his *Diamagnetism and Magne-Crystallic Action.*

He made some very interesting experiments on the effects of compression—that is, on the effects of producing artificially a "line of greatest density" in a particular direction. Perhaps the best of them was made accidentally. He was experimenting with the great electro-magnet of the University of Berlin, the copper helices of which alone weigh 243 lbs. A cube of bismuth was suspended between the poles, and the poles were accidentally brought rather too near together; their mutual attraction overcame the friction between them and the iron pillars on which they lay. They rushed together and crushed the bismuth between them, compressing it to about three-fourths of its former thickness. The poles having been separated and the bismuth extracted, it was boiled in hydro-chloric acid to remove any trace of iron it might have acquired from the poles, and again suspended between them. The line of greatest compression at once set equatorial.

The poles were now purposely allowed to rush together, again pressing the bismuth along a line at right angles to the former line of compression. On being again cleaned and suspended, the new line of compression set equatorial. It was found, by repeating the experiment, that the direction of the magnetic axis could be changed as often as desired.

This experiment was the more remarkable as the bismuth had

* And "Exp. Res.," 2454, vol. iii. p. 83.

previously a natural crystalline structure, but the difference of density in the two directions, produced by the compression, was so much greater than that due to the direction of the cleavage planes, that the set was always determined by the direction of the artificial compression.

Prof. Tyndall fills several memoirs with experiments to confirm and illustrate the law above described.

A paste made of wax and powdered bismuth is an excellent material from which to make artificial crystals by compression. They can also be made by compressing bread, if great care be taken as to the cleanliness both of the fingers and tools employed.

In these experiments it is usually necessary for the experimenter to wash his hands about every five minutes. The hands should be washed under a tap, so as to have a constant change of water, and dried with a "glass-cloth," which is not so liable to get dusty as an ordinary towel.

The following experiment of Prof. Tyndall's on the construction of a model to show the effect of cleavage planes is of interest. Emery-paper is very strongly paramagnetic. Let two bars, each one inch long and half an inch square, be constructed of it. One, which we will call No. 1, is made by gumming together a sufficient number of strips, each one inch by half an inch, to make up the half-inch thickness; the other, which we will call No. 2, by gumming together a sufficient number of pieces, each half an inch square, to make up the inch length. On being suspended between the poles of a magnet, No. 1, which represents a crystal with its cleavage planes parallel to its length, sets axial. No. 2, however, in which the cleavage planes are perpendicular to the length, sets equatorial; that is, with its cleavage planes, and not its length, axial. It is very striking to see the behaviour of No. 2 when the magnet is powerful. The attraction of the mass to the nearest pole is so powerful that once, when the author was repeating the experiment, it broke a stout thread of sewing silk by which the bar was suspended, and yet the length is held very strongly in the equatorial line, the action being exactly that of a homogeneous bar of a strongly diamagnetic substance.

Effects of the Surrounding Medium.

It is found that the medium in which the substance experi-

mented on hangs between the poles affects the result of the experiment. For instance, a homogeneous bar of a feebly paramagnetic substance will point axially in air or a vacuum, but will point equatorially if it is immersed in a strong solution of proto-sulphate of iron.

A series of experiments made by Faraday, and afterwards continued by Tyndall, have given the obvious and simple explanation of the matter. In order that the suspended body may take up any position, it has to displace an equal quantity of the surrounding medium from that position; but the magnetic force acts both upon the substance and upon the medium. If the action upon the substance is stronger than that upon the same quantity of the medium, the substance will take the same position as if it was in a vacuum. If, on the other hand, the magnetic action on the medium is greater than that on the substance, the medium will take the position to which the magnetic force tends to move it, and the substance will be displaced and will take the contrary position.

When this fact was established it was suggested by Faraday that it might be possible to account for all the phenomena of diamagnetism without assuming the existence of a true repulsion, by supposing all space to be filled with a medium whose magnetic capacity was less than that of iron, but greater than that of bismuth, and that the supposed diamagnetic properties of bismuth might be accounted for by considering it merely as a feebler paramagnetic than the medium.

Prof. Tyndall,* in a letter to Faráday, has pointed out that this explanation is not sufficient to account for the observed facts, and in particular that conclusions deduced from it as to magne-crystallic action are directly at variance with the results of experiment. The arguments in favour of the existence of true diamagnetic repulsion are unaffected by the consideration of the effects of the media-surrounded bodies under the action of magnetic forces.

* "Diamagnetism," p. 213.

CHAPTER XXXII.

EXPERIMENTAL DETERMINATION OF EQUIPOTENTIAL LINES AND SURFACES AND LINES OF FLOW.

PROFESSOR W. G. ADAMS'S EXPERIMENTS.*—PLATES XXIX., XXX., XXXI.

PROFESSOR ADAMS has succeeded in experimentally tracing the equipotential curves in conductors through which a current was flowing.

The use of this research is found in the fact that the equipotential curves can be deduced by a mathematical process from the theory of electric distribution, and it was expected that the agreement or disagreement of the experimental with the theoretical results would form a test of the theory.

The general theory of these experiments is based on the fact that, if the two electrodes of a galvanometer be connected to portions of a conductor in the same equipotential surface, no deflection will be produced, however strong a current be flowing in the conductor.

The method of tracing which was employed consisted in causing a current to pass between two points, either in a liquid or in a sheet of tinfoil, and then, having placed one electrode of the galvanometer at a point in the conductor, to determine a number of points for the other where there is no deflection. These points all lie in the same equipotential line or surface as the first point. With a delicate reflecting galvanometer a displacement of an electrode of 1 millim. from its proper position causes a marked deflection of the spot of light. The following is Professor Adams's description of his experiments :—

* See Bakerian Lecture, Proc. Roy. Soc., XXIV., 1875-6, p. 1.

"To trace the curves one electrode of Thomson's reflecting galvanometer was attached to a small screw or pin, fixed in contact with, or passing through the tinfoil disc: and the other galvanometer-electrode was attached to a small tube of the same size as the screw, with the end of which contact could be made at any point of the disc. In the centre of this small tube a needle was held by a spring; and when the required point was found, by pressing down the spring a hole could be made in the tinfoil, thus marking the position of the tracing-electrode."

Fig. 160 shows an arrangement of electrodes used by the present writer for a repetition of Professor Adams's experiments.

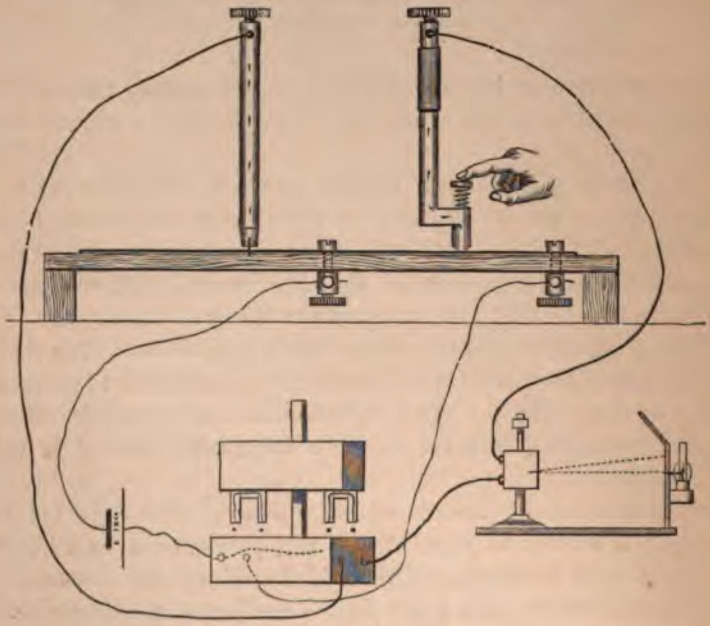


Fig. 160.

The best form of contact is probably by means of needle-points on which shoulders of metal two or three millims. in diameter are soldered, and which are pressed tight on the tinfoil. By placing a sheet of paper underneath the tinfoil disc, the forms of equipotential curves are at once pricked out and may afterwards be drawn. For illustration in lectures, the sheet of tinfoil may be

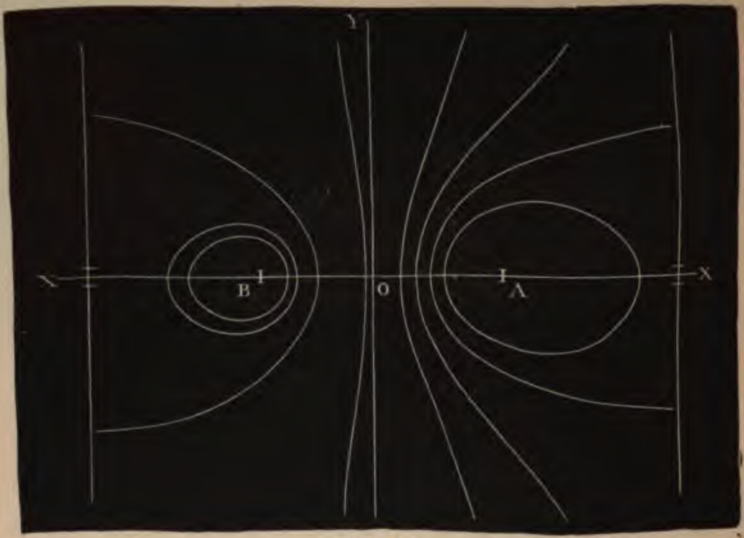


Fig. 1.

Fig. 2.

PLATE XXIX.—EQUIPOTENTIAL LINES.

placed in front of a lamp, and the forms of equipotential curves or lines of flow may be thrown on a screen. If the curves be traced on a circular disc, of the size of, or smaller than, the condensing-lens, the whole series of equipotential curves on it may be thrown on the screen at the same time.

"*Case* 1.—Plate XXIX. (fig. 1) represents a sheet of tinfoil 310 millims. square, in which A and B, the battery poles, are 126 millims. apart; and the line A B is nearly parallel to a side and passes through the centre O of the square; the point O is equidistant from the two poles.

"Not far from the centre of the sheet, and in the smaller curves through an angle varying from 60° to 90° about the electrodes, these curves coincide with circles, and in other parts of the curves, when the influence of the edge is taken into account, the agreement with the curves as given by theory is remarkably exact.

"If a large sheet of tinfoil be taken, and the battery electrodes be placed far away from the edge of the sheet, then at all points not near the edge of the sheet the forms of the equipotential curves will be very nearly the same as in a sheet of infinite extent.

"In all such cases the equipotential curves, when there are only

Fig. 161.

two battery electrodes in connection with the sheet, are circles having their centres on the straight line passing through the two

electrodes; and the lines of flow are also arcs of circles which pass through the two poles.

"*Case* 2.—Fig. 161 represents a circular sheet of tinfoil, 210 millims. in diameter, with the electrodes on the circumference, and at a distance from one another equal to the radius. The electrodes were small binding-screws placed as closely as possible to the edge of the disc. The differences of potential between two successive equipotential curves have been measured by the deflections of the needle of the galvanometer.

"The deflections were as follows:—

From k to a	150
„ a to b	50
„ b to c	50
„ c to e	50
„ e to f	50
„ f to g	50
„ g to h	80

"It will be seen that the fall of potential from k to d is greater than the fall of potential from d to h. This may arise from a difference in the resistances of the contacts with the two battery-electrodes.

"The radii of the circles are 28, 56, 290, 82, 28 and 12 millims., beginning from the point k; and the distances between them, measured along the line joining the electrodes, are 20, 13, 15, 19, 15, 10 and12 millims.

"The distances 13, 15, 19, 15, 10 correspond to equal differences of potential; and hence the resistances of the portions of the disc between these consecutive equipotential curves are equal to one another. In this case there was considerable resistance between the binding-screw and the tinfoil disc at the point of contact; but this does not alter the forms of the equipotential curves.

"*Case* 3.—Plate XXIX., fig. 2, represents a large sheet of tinfoil 18 inches square, with one electrode in the centre, by which the current enters the sheet, and four similar electrodes at four corners of a square, each being three inches from the central electrode, by which the currents leave the sheet. The electrodes were needles with shoulders of brass three millims. in diameter soldered on them.

"The four negative electrodes may be united together beneath the board on which the tinfoil is placed, by strips of copper screwed

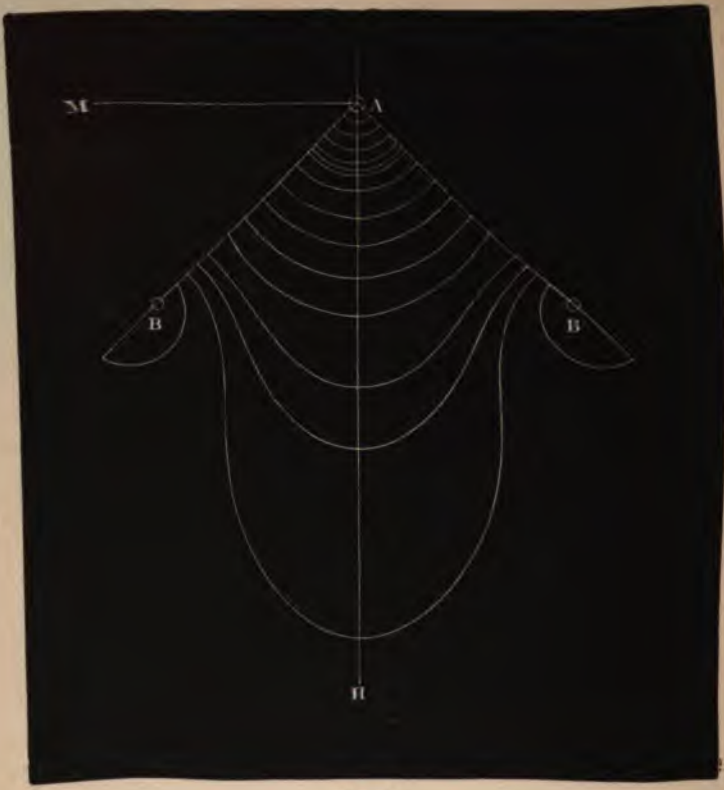


Fig. 1.

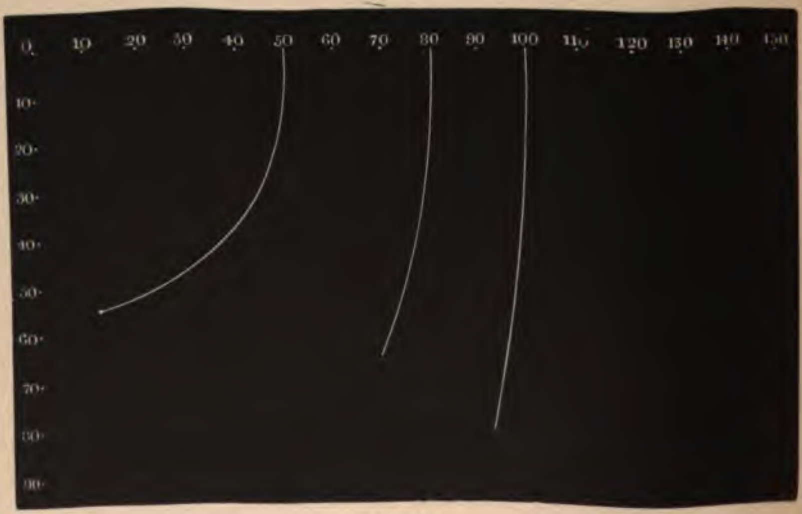


Fig. 2.

PLATE XXX.—EQUIPOTENTIAL LINES.

to the electrodes by a small nut on each needle. On the needles which pass through the tinfoil are shoulders which come down tight on the tinfoil so as to make good contact. For these curves two cells of Grove were used; and the difference of potential between two successive curves causes a deflection of 50 divisions of the scale. The resistances of the portions of this disc between successive equipotential curves are equal to one another.

"*Case* 4.—The curves in Plate XXX., fig. 1, lying within the octant B A H, are equipotential curves, when one positive electrode A is at the corner of a square sheet of tinfoil of which A H and A M are the edges, and one negative electrode at B, at a distance of three inches from A, the line A B bisecting the angle between the two edges. The curves between the lines A B and A M have not been drawn in the figure.

"The curves, with two exceptions, are drawn at distances corresponding to equal differences of potential; so that, omitting the interpolated curves, the resistances of the portions of the sheet between two consecutive equipotential curves are equal to one another.

"This figure also represents the equipotential curves for a square sheet B A B_1, of which A B and A B_1 are the edges, with one positive electrode at A, and two negative electrodes at B and B_1, on the edges of the sheet.

"We may also regard the case with one positive electrode at the centre, and four negative electrodes at the corners of a square as equivalent to two sets, each set consisting of one positive and two negative electrodes, one on each side of it at equal distances along the same straight line on a sheet either unlimited or limited by that straight line.

"*Case* 5.—The curves for this arrangement of electrodes are drawn in Plate XXXI., fig. 1; the distance from the positive to each negative electrode is 76 millims., or 3 inches, as in Cases 3 and 4, the electrodes being near the centre of a very large sheet of tinfoil.

"Taking the curve which cuts the axis at a distance of 54 millims. from the centre, and at distances of 1 millim. on either side, the distances r_1, r_1' from the negative electrodes to the several joints on the curve differ by the quantities in the following table:—

Values of $(r_1 - r_1')$.

For 53 millims.	For 53·75 millims.	For 54 millims.	For 55 millims.
106	108	109	110
105	109	109	110
104	108	110	110
104	108	109	$110\frac{1}{2}$
104	108	112	110
101	108	114	110
99			
97			

"The curve drawn between those at 53 and 54 millimetres was drawn as nearly as possible at a distance of $53\frac{3}{4}$ millims. from the centre.

"The result of this case shows that in the case of one and four electrodes (Plate XXIX., fig. 2), we may expect the curves which cut the axis at a distance of about 54 millims. from the centre to be hyperbolas. The fifth curve from the centre is in the position of the rectangular hyperbola, having its foci in the positions of the negative electrodes; and we find, on measuring this curve as well as the curve on the outside of it, that near the vertex the curves are accurately hyperbolas. This is also true of the corresponding curves in fig. 4. The curves first drawn in fig. 5 were drawn at equal distances of 10 millims. apart along the axis, reckoning from the centre; and the differences of potential for these curves, reckoned from the centre, are proportional to the numbers

138, 85, 88, 100, 80.

138 including the effect due to contact of the electrode. Other curves were afterwards interpolated in the neighbourhood of the position of the rectangular hyperbola and around the negative electrodes.

"The sheet of tinfoil in the last three cases was sufficiently large for the curves in the neighbourhood of the axis to be similar to those which could have been traced on a sheet of infinite extent.

"The third equipotential curve from the negative pole C is the rectangular hyperbola, and its vertex O divides the distance A C; so that

A O is to A B as 1 is to $\sqrt{2}$

A O is equal to 53·75 millimetres.

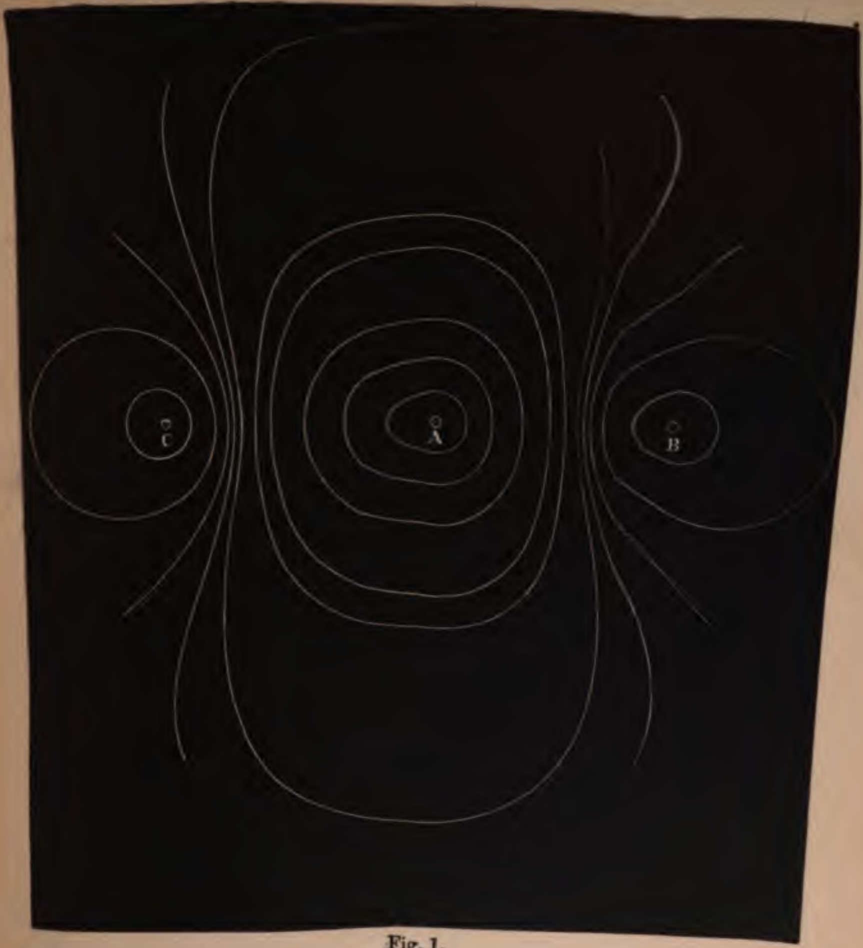


Fig. 1.

Fig. 2.

PLATE XXXI.—EQUIPOTENTIAL LINES.

"*Case* 6.—Fig. 162 represents the case of a circular disc, where the current enters at the edge and leaves at the centre of the disc.

Fig. 162.

"Around the centre the curves are very nearly ellipses of small eccentricity, the focus being at the centre of the disc.*

"When the fixed galvanometer-electrode is at L, it is difficult to find a succession of points forming a continuous equipotential curve; the tracing-electrode may at one time be placed on the boundary of the shaded portion of the figure, and at another may be placed on the axis near the point Q, without causing any current through the galvanometer.

"On placing the fixed galvanometer-electrode at Q, the tracing-electrode marks out two straight lines in the neighbourhood of that point of the same potential as the point Q, and each cutting the edge of the disc at an angle of 45° at that point.

"The uncertainty in tracing this equipotential curve is explained by the fact, that each of the galvanometer-electrodes was rather more than 1 millimetre in diameter.

"The equipotential curves which lie further from the centre cut the edge of the disc at right angles.

* If a is the radius of the disc, and r the distance from the centre, the eccentricity is $\frac{2r}{a}$.

The curve cutting the axis at the point L at a distance of 16 millims., i.e. $(3-2\sqrt{2})\,a$ from the centre, has two branches cutting one another at right angles at the point Q, and each cutting the edge of the disc at an angle of 45°, the radius of the disc being 3·75 inches.

To Determine Experimentally the Lines of Flow and the Equipotential Surfaces in Space of Three Dimensions.

"If two platinum wires, sealed in glass tubes, with only a short piece of wire projecting from the sealed end, be immersed in a liquid, the other ends being connected with the poles of a battery, we shall have a close approximation to the case of currents flowing from one point to another within a liquid; and by means of two other platinum wires similarly arranged, but attached to a galvanometer, we may trace out the forms of equipotential surfaces within the liquid. If dilute sulphuric acid be employed, there will be polarization on the electrodes; but by reversing the current alternately, and making contact only for a short time, the polarization may be kept small on the galvanometer-electrodes, provided they are not moved far away from the same equipotential surface.

"After a few preliminary experiments to determine how far the method was practicable, I began a definite series of experiments in March, 1872. For the experiments in dilute sulphuric acid, in sulphate of copper, and in sulphate of zinc, I have employed a rectangular wooden box, 1 foot long, 8 inches broad, and 8 inches deep. On the edges of the box are fastened paper millimetre scales; a piece is cut out of the middle of the ends of the box, and a sliding piece fitted in to carry the battery electrodes. These sliding pieces are capable of motion parallel to the sides of the box, so as to place the battery-electrodes at different distances

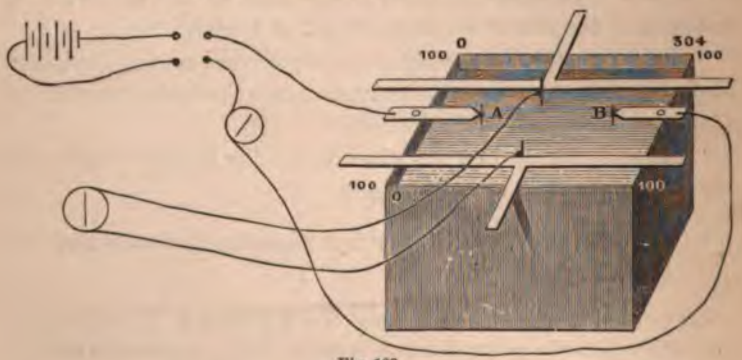


Fig. 163.

from one another (fig. 163). The galvanometer-electrodes were placed firmly in brass tubes, which were accurately placed on

T pieces of wood, so as to be in a line with the point of intersection of two edges of the T piece, and to be vertical when the T pieces are placed on the edges of the box. By this means the rectangular co-ordinates of the point could at once be read off on the sides and ends of the box.

"The first experiments were made with the points at a depth of 10 centims. below the surface, the box being nearly full of liquid. In making the experiments the current was reversed, and the readings of the galvanometer taken on both sides of zero for each position of the electrodes.

"The battery employed was 20 Leclanche cells, the resistance of each cell being nearly 3 ohms, and the electro-motive force about $1\frac{1}{2}$ of Daniell's cell. The strength of the battery current was measured by a tangent-galvanometer of the form of Helmholtz's double galvanometer; the deflection of the needles during these first experiments was generally 46°. The galvanometer-electrodes could be brought up to within 1 centim. of the centre of the box.

"A preliminary series of experiments were then undertaken to determine and eliminate the effect of the polarization currents produced by the action of the electrified liquid of the galvanometer poles, which were not found to be quite so small as had been hoped. These being completed, the equipotential surfaces in three dimensions were traced.

"The plane which is equidistant from the electrodes was shown to be an equipotential surface, namely, that at which the potential is zero.

"*Case* 7.—Plate XXX., fig. 2, represents three sections of three equipotential surfaces, one through the point (50·10), another through the point (80·10), and a third through the point (100·10), the battery-electrodes being placed at distances of 10 millims. from the ends of the box, and 284 millims. apart.

"When the battery-electrodes are so near to the ends of the box, the distribution of the electric currents, and therefore the forms of the equipotential surfaces, will not be the same as in a conductor which is unlimited in every direction; hence in comparing these experimental results with theory it is necessary to take into account the influence of the ends and sides of the box."

We must remember that the line 0—150 in Plate XXX. fig. 2, is the line A B in fig 163.

Experiments with Linear Electrodes.

"*Case* 10.—The rectangular box was also employed to determine the forms of the cylindrical equipotential surfaces when the electrodes are straight rods and extend throughout the depth of the liquid. Sulphate of zinc was employed for these experiments, and the electrodes were amalgamated zinc rods. Plate XXXI., fig. 2, represents the sections of the equipotential surfaces when one battery-electrode is at A, the centre of the box, and the other at B, the middle point of one side. These electrodes are 100 millims. apart. The galvanometer electrodes in these experiments could not be brought within less than 5 millims. of the axis of the curves.

"The curves drawn represent the sections of equipotential cylindrical surfaces which are at distances of 10 millims. apart, measured along a line which is parallel to and 5 millims. distant from the axis.

"The case of a circular cylinder containing sulphate of copper, with the battery-electrodes at the two ends of a diameter, has also been worked out experimentally, and the equipotential surfaces are circular cylinders cutting the sides of the vessel at right angles. Mercury was tried for these experiments, but from its almost perfect conducting-power it was very difficult to determine two vertical lines in it which were precisely of the same potential.

"*Case* 11.—Another case was worked out experimentally with line-electrodes in sulphate of zinc. One positive electrode was placed at the middle point of one side of the rectangular box, and two negative electrodes were placed symmetrically at the same distance from the positive electrode, so that the lines joining the positive to the two negative electrodes were at right angles to one another. This corresponds to the case drawn in Plate XXX., fig. 1, and the sections of the surfaces at points which are not near the side of the box are the same as the curves in Plate XXIX., fig. 2, or Plate XXX., fig. 1. Having previously determined the forms of these curves in the tinfoil experiments, it was very easy to move the tracing-electrode from one point to another on the same equipotential curve, by making use of the curves previously drawn as guides for the electrode."

LINES OF FLOW.

The theory shows that the lines of flow cross the equipotential curves at right angles. Hence the lines of flow can be traced; but, as no electricity crosses a line of flow, or, in other words, as there is no current along an equipotential line, then, if from a sheet of indefinite extent we cut off a portion bounded by lines of flow, we shall not affect the electrical distribution; that is, if the theory is correct, the forms of the equipotential lines will be the same as before the sheet was cut. This was found to be the case, as will be seen on comparing Fig. 1, Plate XXX., and Fig. 2, Plate XXIX., where in Plate XXX. one fourth of the sheet is cut out by the lines of flow joining the electrodes A B, A B′. On deducing the mathematical equation of the lines of flow, it can be shown that they are arcs of circles passing through the battery-electrodes. A comparison of this result with Fig. 1, Plate XXIX., shows a very close accordance between theory and experiment, for a series of circles with their centres on the line Y O Y′ and passing through the points X X, will cut all the curves at right angles. Of course the straight line X X is an arc of the circle whose centre on O Y is at an infinite distance from O.

"The manner in which curves calculated for a sheet of infinite extent are varied near the edge of a sheet not coinciding with a line of flow, is calculated and found to agree very closely with experiment. Some conclusions with regard to the effect of varying the depth of the galvanometer-electrodes in the liquid are shown to agree exactly with experiment.

"The equipotential curves for Case 10, with linear electrodes in the liquid, are theoretically the same as those for Case 5, with points on a sheet of tinfoil for electrodes. A comparison of the figures (Plate XXXI., figs. 1 and 2), which are laid down from the experimental results, shows how closely they agree, and may be taken to be an independent proof of the accuracy of the theory of electrical distribution.

"It is interesting to know that the conduction of a current in an electrolyte resembles that of a current in a metallic conductor as far as the lines of flow are concerned."

CHAPTER XXXIII.

THE INDUCTION COIL.

We have seen, in Chapter XXII., that if a magnet be placed inside a coil of wire and suddenly withdrawn, a momentary current of electricity will be produced in the coil, and that its electromotive force will be greater the more suddenly the magnet is drawn out.

If, instead of removing the magnet, we destroy its magnetism, we find, as we might expect, that a current is still induced in the coil. If, instead of a steel magnet, we use an electro-magnet, we can, by starting and stopping the current, make and destroy the magnetism much more suddenly than we can insert and withdraw a steel bar; and so, on the destruction of the magnetism, we shall induce a current in a surrounding coil having a much greater electro-motive force than could be produced by the withdrawal of a steel magnet of equal strength.

The induction coil is an instrument in which advantage is taken of the fact of electro-magnetic induction, to convert the electricity of the voltaic battery current, which has large chemical, heating, and magnetic effects, but of which the greatest difference of potential between its different points is comparatively very small, into electricity with much less chemical and magnetic power, but of which the difference of potential at different points in the circuit is enormous.

In order to obtain some idea of the difference between the electro-motive forces given by a battery through the medium of a coil and those of the largest batteries directly, we may note that Messrs. De La Rue, Müller, and Spottiswoode,* found that with 1080 chloride of silver cells, it was only possible to obtain a spark, whose length varied from $\frac{1}{263}$ inch (0·096 millim.), to

* Proc. Roy. Soc., vol. xxiii. 1875, p. 357.

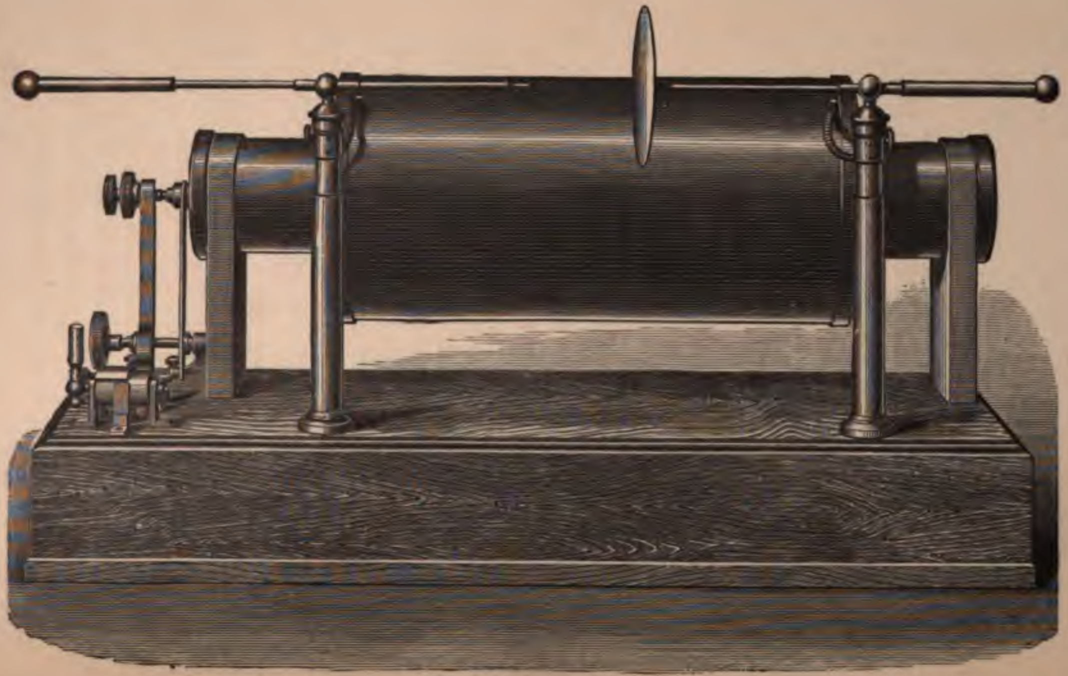


PLATE XXXII.—17-INCH INDUCTION COIL.

$\frac{1}{250}$ inch (0·1 millim.), while even small induction coils give sparks of over an inch with one or two cells—and Mr. Spottiswoode's great coil, which is described below, gives, with 50 Bunsen cells, a spark of $42\frac{1}{2}$ inches, or more than a metre.

The induction coil consists mainly of an electro-magnet placed inside a coil of fine wire and an apparatus for magnetizing, and demagnetizing the electro-magnet as rapidly as may be desired.

The following is the general outline of its construction. A core of soft iron is covered by an insulating material, and round it are wound a few layers of stout insulated wire, in the form of a helix. This helix is called the *primary coil.* Outside it and well insulated from it by means of a thick ebonite tube, is wound a very great length of very fine insulated wire, forming a great number of layers, each of which consists of a great many windings. The fine wire is called the *secondary coil.*

The *core* is usually made of a bundle of iron wires, as they will demagnetize more quickly than a solid bar.

The ends of the primary wire are connected to a battery, the ends of the secondary to discharging points separated by a greater or less interval of air. When the current is made or broken in the primary circuit, a certain difference of potential is caused by induction along each portion of the secondary circuit, each winding being acted on by the iron core, and by the portions of the primary circuit near to it.

There are a great number of windings of the secondary, and a separate difference of potential is produced in each. These being all added together produce a very great difference of potential at the discharging points, which difference is sufficient to break down the resistance of the air between the points.

Plate XXXII. represents a coil, by Apps, in the possession of the author, which gives a spark of 17 inches in air, and has 22 miles of secondary wire.

It is very necessary that contact should be broken as suddenly as possible, in order that the differences of potential produced at different points of the secondary circuit may all act at once in producing a great difference of potential at the extremities.

It is found that, except in very large coils, sparks are only produced on breaking the circuit, and even in very large coils the spark produced by closing is much feebler than that produced by opening. This may be due to the fact that the magnetization of

the iron core takes longer to rise to its maximum value than to sink from its maximum to zero.

The Condenser.*

This is a very important portion of an induction coil. It consists of a number of sheets of tinfoil, separated by mica, gutta-percha, or paraffined paper. The 1st, 3rd, 5th, 7th, &c., sheets are connected to one end of the primary wire, the 2nd, 4th, 6th, 8th, &c., to the other end. When the circuit is broken, the extra current,† induced in the primary wire by breaking, is in the same direction as the primary current, and therefore tends to prolong the magnetization of the core. When a condenser is used, the extra current spends itself in charging it. The condenser then, instantly discharging itself, sends a current in the reverse direction round the core, and at once demagnetizes it. The condenser is usually placed in the base of the coil.

Contact Breakers.

THE VIBRATOR.

Various methods are used to make and break the circuit.

The form of contact breaker which is universally used for small coils is called the vibrator (fig. 164).

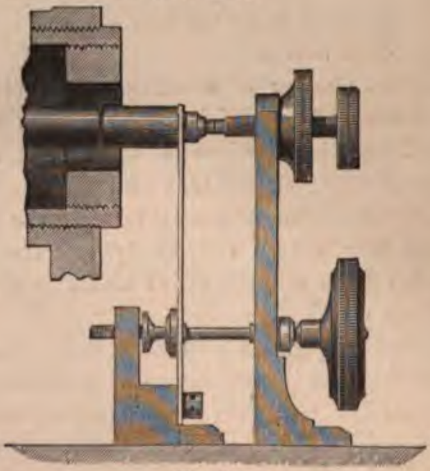


Fig. 164.

It consists of a piece of iron, which is supported near one end

* See vol. i. p. 66. † See vol. i. p. 309.

of the core by a brass or steel spring, which tends to pull it away from the core, and to force a piece of platinum soldered on to the back of the spring against a platinum pointed stop. The position of the latter can be regulated by a screw. The primary current passes from the stop to the spring.

A second screw regulates the tightness of the spring. This

Fig. 165.

tightening screw works in an ivory collar for insulation, and usually has an ebonite head.

When the current passes, the iron core becomes a magnet, and, pulling the spring forward, separates the platinum points and breaks the current. This, at the same time, destroys the magnetism of the core, and the spring flies back and completes the circuit, when the process is repeated, and thus a constant vibra-

tion is kept up. When the spring is weak, the current is broken at a time when the core has but small magnetic strength, and a feeble induction current is produced. By tightening the spring we may arrange the apparatus so that the current is not broken till the core has received nearly its maximum of magnetization, and so a much stronger current of induction is generated.

The advantage of the vibrator is that, while using a strong battery, we can obtain either a very feeble spark, or nearly the maximum power of the coil, without altering the battery—the difference being made by simply turning the handle of the tightening screw. The vibrator is not suitable for very large coils, owing to the heating effect of the spark of the extra current at the point of make and break, which is sufficient to fuse the platinum points, and to damage the coil; this spark also destroys the suddenness of the break, for flame is a conductor of electricity.

Fig. 166.

A coil giving a 17-inch spark is about the largest size for which the vibrator can be employed with safety.*

* Mr. Apps informs me that he has just succeeded in using a vibrator for a coil giving 26 inches spark.—March, 1880.

Clock and Hand Breaks.

In these instruments a platinum plunger is lifted in and out of an amalgam of mercury and platinum at the bottom of a glass vessel, the upper part of which is full of alcohol, placed there to extinguish the extra current spark. In the hand-break, fig. 165, the plunger is pressed down (to make contact) by hand, and raised again by a spring. In the clock break, fig. 166, the plunger is raised and lowered by a crank attached to a clock. The speed of the clock is regulated by means of fans which can be turned so as to offer greater or less resistance to the air.

The drawings are from breaks by Apps.

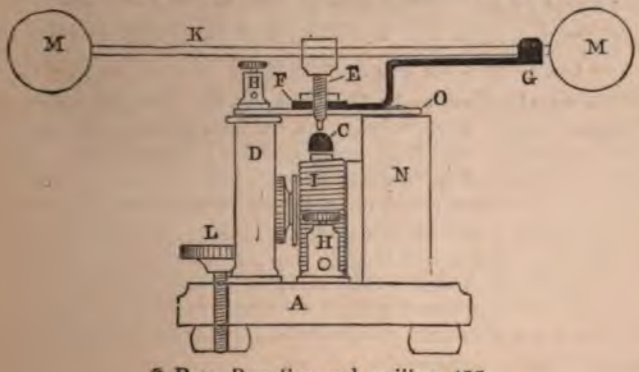
Spottiswoode's Wheel Break.

This is used for vacuum tube experiments. Its object is to make and break contact very rapidly. It consists of a brass wheel with a number of radial slits filled with ebonite. A light platinum spring presses on the circumference, and is held in a clamp lined with india-rubber to deaden its vibrations. When the wheel revolves, contact is broken as each slit passes the spring. There is a small pulley on the axis of the wheel round which the driving-band passes. The band may either be connected to a fly-wheel turned by hand, or, as in Mr. Spottiswoode's laboratory, to a small steam-engine.

Spottiswoode's Rapid Break.*

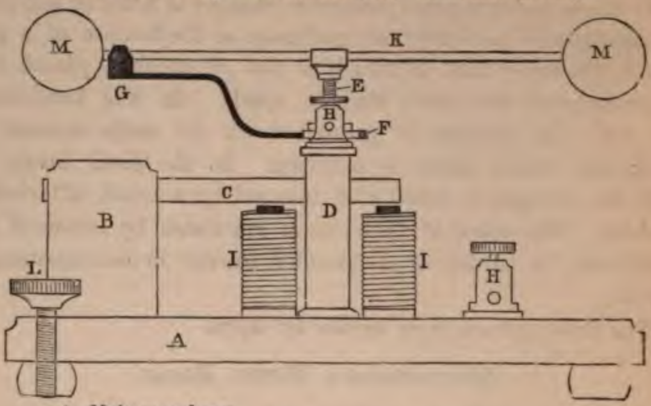
Fig. 167.

End elevation of Contact-breaker. Half size (linear).



* Proc. Roy. Soc., vol. xxiii. p. 455.

Fig. 168.
Side elevation of Contact-breaker. Half size (linear).



A. Mahogany base.
B. Heavy brass column for supporting vibrating spring.
C. Vibrating spring.
D. Brass column for supporting horizontal plate O.
E. Platinum-tipped screw for contacts.
F. Friction-collar for holding steadying-arm.
G. Steadying-arm.
H H. Terminals.
I I. Electro-magnet.
K. Lever-arm for fine adjustment.
L. Levelling-screw.
M M. Compensating weights.
N. Wooden pillar for electro-magnet.

This is a particular form of break which has been used by Mr. Spottiswoode for vacuum-tube experiments. The contacts are made and broken by the vibrations of a short stout steel rod rigidly fixed at one end, and kept in action by a small independent electro-magnet. The number of vibrations per second made by the different rods tried, under the action of the magnet, varied from 700 to 2500. The amplitude of each vibration was not more than $\frac{1}{100}$ of an inch.*

* With regard to these breaks, Mr. Ward, Mr. Spottiswoode's assistant, who invented the "rapid" break, writes to me, "One feature about the 'rapid' and 'wheel' breaks is the exceedingly small quantity yielded by them. In some small coils the length of spark, with a vibrating break, is about $\frac{1}{10}$ inch, and you cannot bear to have that passed through your body, as the shock is so great. In using my rapid break with larger coils, you can get discharges $\frac{1}{4}$ and $\frac{3}{8}$ long, which you can pass fearlessly through any part of the body. I also noticed the comparatively high static quality of spark in another form—that is, the way in which the electrodes of the coil attract pieces of paper, &c., and the way in which the wires from the electrodes, if they be free to move, attract one another at great distances."

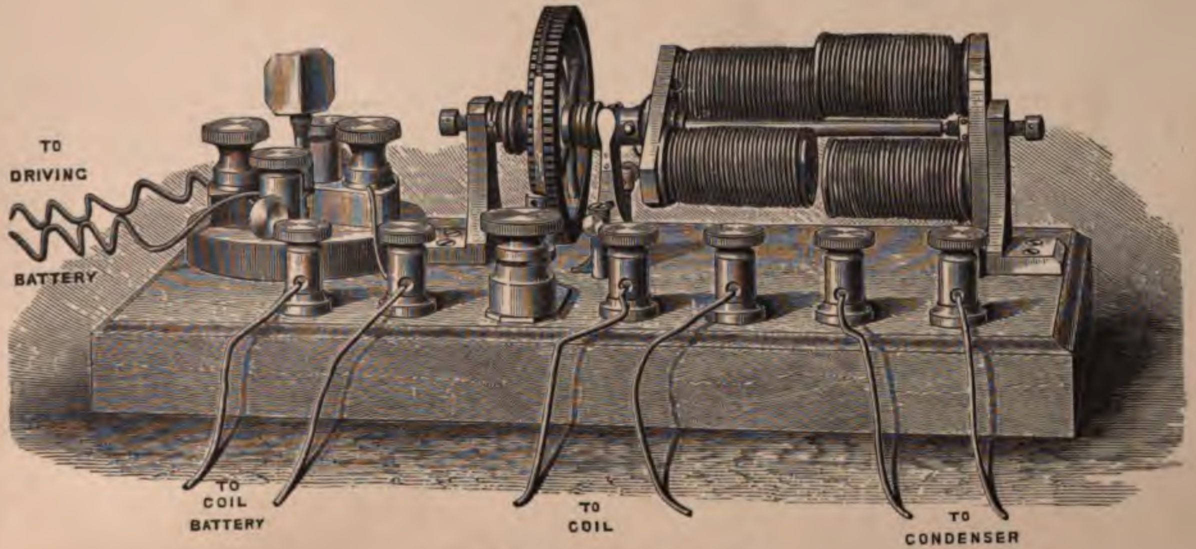


PLATE XXXIII.—HIGH-SPEED BREAK.

GORDON'S HIGH-SPEED BREAK.—PLATE XXXIII.

The present writer has arranged a break for experiments on specific inductive capacity in which an enormous speed was required (see vol. ii. page 112). It consists of a little electro-magnetic engine,* the fly-wheel of which is about two inches diameter. Sixty slits are cut in its circumference and filled with ebonite; a light spring presses on it, and the primary current on its way from the battery to the coil is made to pass from the spring to the wheel. When the wheel revolves, the current is closed sixty times and broken sixty times during each revolution.

When the engine is driven by four large Grove's cells, the fly-wheel revolves just 100 times per second, so that the primary current is made 6000 times and broken 6000 times in each second.

MR. SPOTTISWOODE'S COIL.—PLATE XXXIV.

A description of this, the largest coil ever constructed, will be found in the Philosophical Magazine for January, 1877.

It was made by Mr. Apps. The total weight of the coil is 15 cwt.; its length 4 feet; its external diameter 20 inches. It is supported on two massive pillars at its ends, while a central pillar, adjusted by a screw, provides against any bending that may occur.

There are two primaries, one of which may be replaced by the other by two men in the course of a few minutes. The one to be used for long sparks, and for most experiments, has a core consisting of a bundle of iron wires, 44 inches long, by 3·56 inches in diameter, and weighing 67 lbs.

The copper wire of this primary is 660 yds. long, ·096 inch (nearly $\frac{1}{10}$ inch) in diameter, and has a total resistance of 2·3 B.A.U., with a conductivity of 93 per cent. It contains 1344 turns, wound in six layers; its weight is 55 lbs., and total length 42 inches. The other primary, which is intended for short thick sparks, has a thicker core, weighing 92 lbs., and the wire is wound in double strands, so as to give much less resistance.

The secondary coil consists of no less than 280 miles of wire forming a cylinder 37·5 inches long, and 20 inches external diameter. The total resistance is 110200 B.A.U. It is wound in

* See Chapter XL.

four sections. The diameter of the wire used for the two central sections being ·0095 (nearly $\frac{1}{100}$ inch) and those of the external a little thicker.

The object of the increased thickness of the wire near the ends is to provide for the accumulated charge which that portion of the wire has to carry. The total number of windings of the secondary is 341,850. In this as in all other large coils made by Mr. Apps, the secondary is wound in a number of discs separated by plates of ebonite. The reason of this is that when a coil is wound in layers, portions of the wire, whose potential are very different, are near together, and a great strain is put on the insulation. When the wire is wound in discs, the portions whose potentials differ very much are separated by the ebonite plates.

It was found that the condenser required was much smaller than might have been expected. One of the same size as that used for a coil giving a 10-inch spark proved to be most suitable. It consists of 126 sheets of tinfoil 18 × 18·25 inches, separated by varnished paper.

Using the smaller primary, this coil gave :—

With 5 quart cells of Grove a spark of				28 inches.
With 10	,,	,,	,,	35 inches.
With 30	,,	,,	,,	42½ inches.

A spark of 42½ inches is by far the largest that has been obtained by any electrical apparatus whatever.

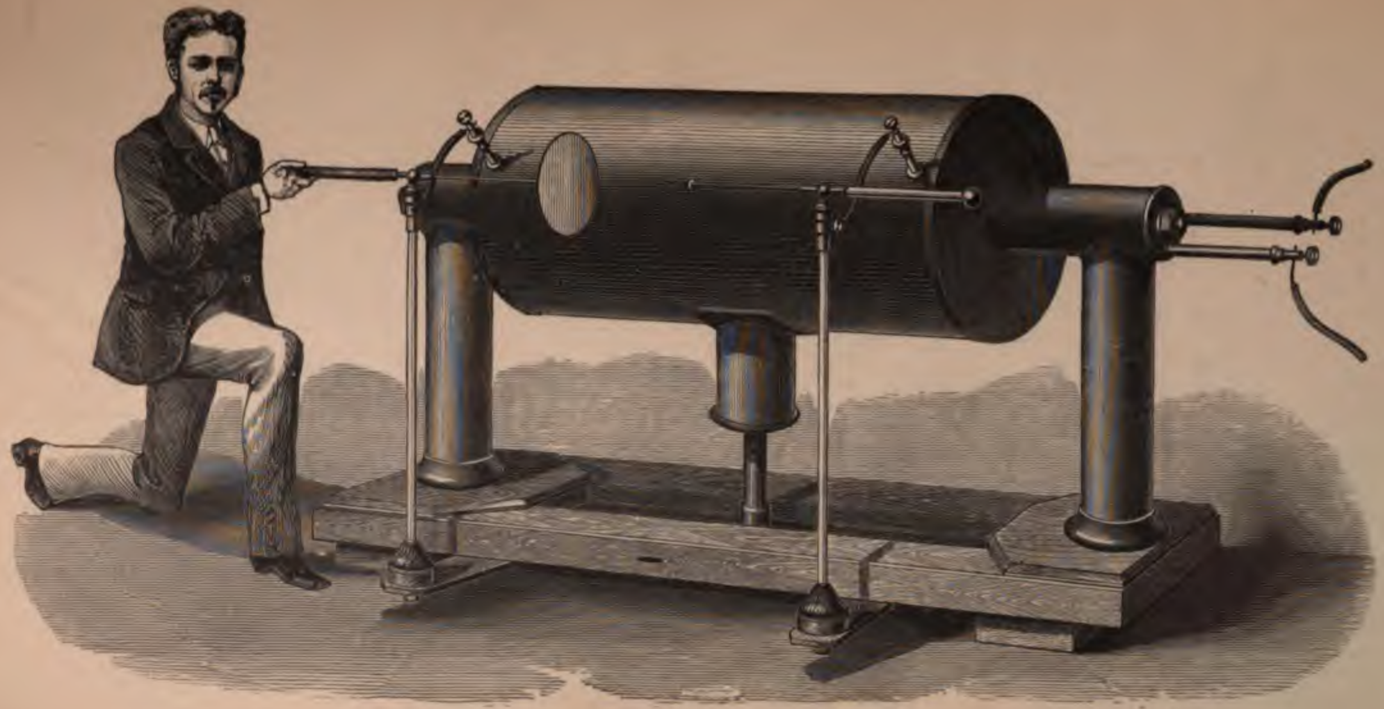


PLATE XXXIV.—MR. SPOTTISWOODE'S GREAT COIL.

CHAPTER XXXIV.

ON THE DISCHARGE OF THE INDUCTION COIL AND DISCHARGE GENERALLY.

THE discharge of the induction coil presents many analogies with that of electric machines, particularly of the Holtz form, and accounts of the appearances seen in discharging the one will frequently, though not always, be applicable to the other.

The phenomena about to be described have, except where the contrary is stated, been observed with the 17-inch coil (Plate XXXII.), worked by 10 quart Grove cells, in series. When the discharge is taken between a point and a disc separated to the maximum distance over which a spark will pass, and the point is made positive, the discharge consists of a zigzag line of bluish white light, and is accompanied by two distinct sounds; one, a crackling which, when a slow working break is used, resolves itself into a separate sharp report like that of a small percussion cap at the instant of each discharge; and the other a hissing sound, caused by the appreciable time required by the 22 miles of secondary wire to discharge itself.

This last effect is more particularly noticeable when the points are near. In Mr. Spottiswoode's great coil, when the points are placed four or five inches apart, the hissing discharge lasts some two seconds or more. When the point is positive, the discharge always takes place near the centre of the disc, but seldom twice in exactly the same spot. When the current is reversed so as to make the disc positive, then with the same battery power only a much shorter spark can be obtained, and it takes place between the point and the edges of the disc. I am not aware that the reason of this difference is known.

When the battery power is weakened, or the vibrator spring relaxed so that the coil will not give quite its full spark, then, if the discharging rods be separated to rather a greater distance

than that over which the spark can pass, the space between will, if the room be darkened, be observed to glow with a faint blue light, extending for some 2 or 3 inches in all directions round the line joining the poles. This has been called the brush discharge.

When the points are put at about the maximum distance over which a spark can pass, the spark and brush discharge are frequently observed together.

When the points are brought within some 2 or 3 inches of each other, the discharge is thicker but nearly silent, and is surrounded by a mass of yellow flame of some $\frac{1}{2}$ inch to $\frac{3}{4}$ inch thick. This is caused chiefly by the combustion of the sodium in the air. It can be blown away by a current of air, leaving the spark unaffected. A candle or piece of paper can be lighted at it.

The discharge from even a very small coil, if taken through the body, produces violent pain and muscular contraction, the patient being usually unable to leave go of the electrodes. The discharge of such a coil as the 17-inch would probably be fatal; indeed, that of a coil giving a $\frac{1}{4}$-inch spark is the maximum that could be taken with safety.*

If an ordinary looking-glass, about 15 inches by 10 inches, be set with its back against the disc of a 17-inch coil, and the point be put near the middle of the glass face, a very beautiful effect is observed. The discharge appears to strike the glass, and breaks in a kind of spray of fire, streaming in every direction to the edges, whence it is conducted by the mercury and wooden back, to the disc.

By placing the points of the secondary at opposite sides of pieces of plate-glass, and surrounding the terminals with cement, considerable thickness of plate-glass can be perforated. With the great Polytechnic coil, only smaller than Mr. Spottiswoode's, 5 inches of glass were perforated. Mr. Spottiswoode as yet has only tried perforating 3 inches, but he found that it only took a 28-inch spark, produced by 5 quart cells, to do it. He calculates that with a 42-inch spark he could perforate 6 inches.

* With the great coil made by Mr. Apps for the Polytechnic Institution, which gave 29 inches spark, a shock was administered to a rabbit without causing death. It is probable, however, as the rabbit was much less than 29 inches long, that the greater part of the discharge passed round him through the air and not through his body.

Discharge with the Rapid Break.

By using one of the rapid breaks, *equal* alternate electrifications can be obtained. A large coil and a small battery must be employed.

With the 17-inch coil, worked by ten small Leclanché cells in series, and the high-speed break (Plate XXXIII.), the electrifications of the secondary poles can be reversed some 12,000 times per second, and the make and break current are found to be nearly exactly of equal strength. A spark of about $\frac{1}{25}$ inch is obtained, which corresponds to an electro-motive force of about 2050 chloride of silver cells.*

Secondary Condenser.

If wires be led from the secondary terminals to the opposite coatings of a Leyden jar, or other condenser, the character of the discharge is changed. The discharges are not quite so frequent, as the jar has to be charged between each spark, but the spark is of a dazzling white, and instead of the usual smart crackle of the impinging sparks, a series of deafening reports are heard. If a slow working break is used, so that there is an interval between each discharge, the metal disc is heard to ring after each spark, as if it had been struck by a hammer.

A secondary condenser is always used for spectroscopic experiments, as the spark has great deflagrating power. When a spark is taken between a point and a polished plated disc, each discharge causes a minute dot on the bright surface, which cannot be rubbed off. It is due to the volatilization and burning of a small portion of the silver. Instead of a single Leyden jar, several connected either "for quantity" or "in cascade" may be used. The latter plan gives the best results.†

The noise caused by a ½-gallon jar, with a 17-inch coil, is sufficient to make it necessary to shout in order to be heard.

* See Phil. Trans., 1879, pp. 419 and 423.

† Leyden jars are said to be connected for "quantity" when all the inner coatings are connected to one pole, and all the outer to the other. When jars are arranged in "cascade," the inner coating of the first is connected to one pole, and its outer coating to the inner coating of the second. The outer coating of the second is connected to the inner one of the third, and so on. The outer coating of the last is connected to the other pole. All jars connected in *any* way to large coils must be placed on insulating stands, and *not* connected to earth.

At the same time, as the strength of the spark is increased, the length is decreased. With a large jar in my possession, which contains 11 gallons, and has 7½ square feet of coated surface, the maximum spark which the 17-inch coil will give is something under 1 inch. With small jars, the length of the spark is limited by the size of the uncoated portions of the jars, as when the points are separated by more than a certain distance the spark springs round the glass. With a ½-gallon jar of the shape usually sold, about 5 inches spark can be obtained.

The jar discharge will perforate paper, but not ignite it.

Induction Coil and Magneto Electric or "Dynamo" Machine.

In November, 1879, Mr. Spottiswoode * published an account of some experiments, in which a 20-inch coil was excited by means of the current produced by De Méritens' dynamo machine,† worked by a 3½ horse-power gas-engine. This machine gives *alternate* currents whose direction is reversed about $16 \times 1300 = 20{,}800$ times per minute, and therefore no contact breaker or primary condenser are required.

This method of working gives secondary currents having great "quantity."

With a 20-inch coil the spark is about 7 inches long, and has the "full thickness of an ordinary cedar pencil." The discharge is extremely regular, and can be used for spectroscopic purposes without a secondary condenser.

Discharge in Rarefied Air.

When the discharge either of a coil or electrical machine is passed through a tube, or other vessel connected to an air-pump, it is found that as the pressure diminishes the length of spark which can be obtained increases. A great many experiments have been made to determine the exact law according to which the spark length increases as the pressure diminishes.

In 1834, Sir Wm. Snow Harris stated‡ that, other things being equal, the length of the spark which an electric machine or Leyden jar will give in air varies in the simple inverse ratio of the pressure. He however gave no tables or figures in support of his law.

* Phil. Mag., 1879, p. 390.

† See Chapter XL.

‡ Phil. Trans., 1834.

In the experiments made by M. Masson,* the spark passed either between two balls in the air, or between two similar balls inside a globe in which a more or less complete vacuum could be produced. The distances between the balls could be varied, as well as the pressures. Within the limits of his experiments, M. Masson found that the length of spark was inversely proportional to the pressure. The greatest length of spark which he used was 11·1 millims.

In 1843 M. Knochenhauer† worked with a constant length of spark of about ¾ inch,‡ and measured the electric density required to produce a spark in air at various pressures. Within the limits of his experiments he found that the ratio of the electric density required to produce a spark, to the pressure of the air, increases sensibly as the pressure diminishes. Now the length of spark is proportional to the electric density; and therefore Knochenhauer's results show that the law given by Harris and Masson does not hold for all distances and pressures.

Wiedemann and Ruhemann§ found a purely empirical formula for variations in the lengths of sparks where the longest spark was 9·95 millims.

Gordon's Experiments.

At the Dublin Meeting of the British Association the present writer gave an account|| of some recent experiments which he has made on the subject. In them an attempt has been made to determine the ratio of the spark-length to the pressure for distances ranging from 6 inches to 30 inches by means of one and the same apparatus. The experiments differ from any former experiments with which the author is acquainted, in the fact that an induction coil was used as the source of electricity instead of an electric machine.

Apparatus used.

The coil was the 17-inch coil already mentioned (Plate XXXII.).

* "Annales de Chimie," 3e série, t. xxx.; or Mascart, "Electricité Statique," t. ii. p. 94.

† Pogg. "Ann." lviii. p. 219; or Mascart, t. ii. p. 95.

‡ He does not state the length of spark he used, but gives the height of his whole apparatus, and a drawing which, if it is to scale, shows that the discharging balls were about ¾ inch apart.

§ Mascart, t. ii. p. 97.

|| Phil. Mag., Sept. 1878, p. 185. Abstract in B. A. Report, 1878, p. 433.

It was worked by 10 quart cells of Grove's battery arranged in series. It was provided with a vibrator and with a clock contact-breaker, either of which could be used.

The Air-Pump was of the ordinary Tait's construction.

The Discharging Tubes.—These consisted of two cylindrical glass tubes about 4 feet (1·33 metre) long and nearly 3 inches diameter. At one end of each was a tap, the brass pipe from which ended in a ball which formed one of the discharging terminals. Holes in the side of the brass pipe admitted the air from the tap to the tube. At the other end of each tube was a stuffing-box, in which a brass rod slid; at the end of the brass rod was a point which could either be placed in contact with the ball or withdrawn some 3 feet from it. The end of the rod was kept always in the axis of the tube by means of three little glass arms, which were inserted into an ebonite collar fixed on the discharging rod a little behind the point. The two tubes were supported in a horizontal position, parallel to each other and about 18 inches apart, on four ebonite legs about 18 inches high. The tubes were joined to the air-pump by means of the pipes and taps shown in fig. 169, which were so arranged that the

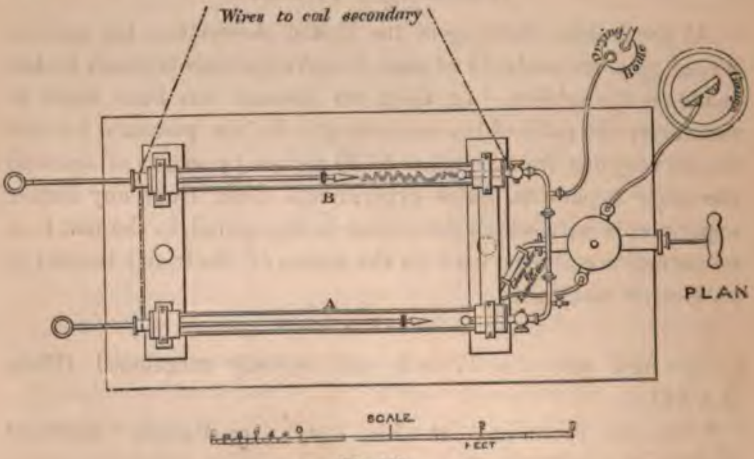


Fig. 169.

tubes could be quickly connected to each other, to the external air, to a gas-holder, or to the pump. Between the tubes and the pump the metal pipe was cut, and a piece of glass tubing about 18 inches long, well varnished with shellac, was inserted,

so that the electricity might not pass to earth through the pump.*

The Experiments.

When the tubes were shut off from the pump, air could always be let into the glass pipe to prevent the discharge passing to earth inside it, as it would do at low pressures. The distance between the point and ball in each tube was measured as follows:—They were placed in contact, and an ink-mark was made on the discharging rod just outside the collar of the stuffing-box. When the rod was slid out, the distance of this mark from the collar was equal to the distance between the point and ball. The pressure was given by a U-gauge, about 4 feet high, attached to the air-pump at one end, open to the air at the other.

The pressure P was given by the formula—

$$P = \{\text{height of barometer}\} - \{\text{difference of level of mercury in the two arms of the U}\}.$$

Before being admitted into the tubes, the air was dried by being drawn through sulphuric acid. When it was desired that the pressure of the air in the tube should equal that of the external atmosphere, air bubbled through the acid as long as the difference of pressure inside and outside the tube exceeded that of the inch of acid which had to be displaced, and then the tap was opened direct to the outside air. The external diameters of the tubes were about 2·94 and 2·76 inches respectively, and the diameters of the balls ·94 and ·92 inch.

In the experiments, one of the tubes (A) was left open to the atmosphere, and its discharging point placed at a standard distance either 6, 8, or 10 inches from the ball; and the other tube (B) being nearly exhausted, experiments were commenced at the low pressure, and then a little air was let in between each observation. The tubes were so connected to the coil that the discharge would pass in whichever tube offered least resistance. The discharging distance in B was then varied and adjusted to the *shortest* distance, which caused the whole discharge to pass in A. This distance having been noted, the points in B were brought nearer together till they reached the *longest* distance at which

* Mr. Apps informs me that it is injurious to the coil to connect either secondary terminal to earth when using long sparks.

the whole discharge passed in B.* The mean of these two distances was taken as the distance which, at the pressure then being worked with, interposed in B a "resistance" equal to that of the standard length in A of air at the pressure of the atmosphere.

Let us call this mean, "mean B spark." Now, if the law that the spark-length is inversely proportional to the pressure holds, we should have for the same series of experiments—

$$\{\text{mean B spark}\}\ \{\text{pressure in B}\} = \text{const.};$$

and to compare different sets made with different distances in A and with the barometer at different heights, we should have—

$$\frac{\{\text{mean B spark}\}\ \{\text{pressure in B}\}}{\{\text{distance in A}\}\ \{\text{height of barometer}\}} = \text{const.}$$

If the two tubes and the discharging points were precisely alike, this constant would be unity. Any slight difference in the shape of the points and balls would cause it to differ from unity, but would not affect its constancy.

Results.

The table (pp. 60, 61), which explains itself, gives the results of several sets of experiments arranged in ascending order of pressures.

The results which I deduce from it are :—

(1) From a pressure of about 11 inches up to that of the atmosphere Harris's law approximately holds good. No variation from it indicating any other law is observed.

(2) No law can be said to be more than approximately true; for when the density has almost reached the discharging limit, any slight accidental circumstance, such as the presence of a grain of dust, a little burning of the point by the last discharge, &c., will cause the discharge to take place. Professor Clerk Maxwell has compared this experiment to the splitting of a piece of wood by a wedge. It is possible to determine the average pressure on the wedge which will split the wood; but in any particular experiment it is impossible to say that the wood will split exactly at that pressure.

(3) When the pressure is diminished below 11 inches, the

* The fact that the discharge only divided itself between the two tubes, when the "resistances" were almost equal, confirms Mr. De La Rue's discovery (vol. ii. page 82) that disruptive discharges do not obey Ohm's law.

product in column VII. rapidly diminishes. This shows that at low pressures the spark produced by a given electro-motive force is much shorter than is required by Harris's law, or that the electro-motive force required to produce a spark of given length is at low pressures greater than that required by Harris's law. This agrees with what Mr. De La Rue has shown (vol. ii. page 82), namely, that at all pressures, however low, the discharge is disruptive, and none of it passes by conduction. If any portion could at low pressures pass by conduction, we might expect that a smaller and not a greater electro-motive force would be required than that calculated by Harris's law from experiments at high pressures.

Sir Wm. Thomson's Experiments.

It is interesting to compare these results with Sir William Thomson's historical experiments "On the Electro-motive Force required to produce a Spark." *

In these experiments the potential or electro-motive force required to produce a spark was measured by an absolute electrometer.† The following table of results was obtained:—

Length of spark in inches. S.	Electromotive force (in arbitrary units). E.M.F.	Electromotive force per inch of air (in arbitrary units), that is, $\frac{\text{E.M.F.}}{\text{S.}}$
Inches.		
·007	2·4495	349·9
·0105	3·0000	285 7
·0115	3 1622	275·0
014	3 6055	257·5
·017	4·0000	235·3
·018	4·3589	242 2
·024	5·4772	228·2
·0295	6·3245	214·4
·034 ·	7·0710	208·0
·0385	7·7459	201·2
·041	8·3666	204·1
·0445	8·9442	201·0
·048	9·4868	197·6
·052	10·0000	192·3
·055	10·4880	190·7
·058	10·9544	188·9
·060	11·4017	190·0

* "Papers on Electro-statics and Magnetism," p. 247; Proc. Roy. Soc., 1860, vol. x. p. 326; Phil. Mag., 1860, 2nd half-year.

† Vol. i. p. 55.

EFFECT OF PRESSURE ON SPARK LENGTH—GORDON'S EXPERIMENTS.

I. Pressure in B = height of barometer minus difference of heights of columns of mercury in the U gauge.	II. Distance apart of points in B which caused the discharge to take place wholly in A.	III. Distance apart of points in B which caused the discharge to take place wholly in B.	IV. Mean of columns II. and III. equal to length of spark which is, at pressure of column I., produced by the same electromotive force which produces a spark in air of length given in column V. when barometer stands at height given in column VI. "Mean B spark."	V. Distance apart of points in A.	VI. Barometer = pressure in A.	VII. $\frac{\text{Length of spark in B} \times \text{pressure in B}}{\text{Length of spark in A} \times \text{pressure in A}} = \frac{(\text{column IV.}) \times (\text{column I.})}{(\text{column V.}) \times (\text{column VI.})}$.
Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	
2·42	30·6	22·9	26·75	6	29·64	·364
3·2	36·1	25·5	30·8	10	29·70	·332
4·59	22·7	18·6	20·65	6	29·64	·533
7·8	26·8	21·4	23·9	10	29·70	·627
7·82	22·0	16·6	19·3	8	29·65	·636
9·34	21·1	19·45	20·62	8	29·65	·812
9·49	17·7	16·2	16·95	6	29·64	·904
11·68	19·0	16·8	17·9	8	29·65	·881
11·74	17·2	16·0	16·6	6	29·64	1·095
11·9	13·7	11·8	12·75	6	29·60	·854
11·9	23·8	19·4	21·6	10	29·70	·928
13·5	15·2	13·9	14·55	8	29·50	·821
14·24	14·2	13·3	13·75	6	29·64	1·101
14·29	18·8	15·8	16·3	8	29·65	·982
14·4	23·2	18·8	21·0	10	29.70	1·020
15·1	15·2	13·9	14·55	8	29·50	·931
15·1	12·4	11·2	11·8	6	29 60	1·003
16·05	12·6	12·3	12.45	6	29·64	1·065
16·24	14·9	14·0	14·45	8	29·65	·989
16·3	19·0	16.0	17·5	10	29·70	·960
16·7	15·2	13·3	11·3	8	29·50	·799

17·6	19·1	17·2	18·1	10	29·70	1·072
17·64	11·7	11·1	11·4	6	29·64	1 181
18·2	12·1	10·7	11·4	6	29·00	1·168
18·4	14·8	12·7	18·75	8	29·50	1·072
18·75	13 0	11·6	12·8	8	29·65	972
19·49	11·3	9·2	10·25	6	29·64	1·123
19·6	16·7	15·3	16·0	10	29·70	1·085
19 8	13·6	11·6	12·6	8	29·50	1·057
20·7	10·6	9·4	10·0	6	29·60	1·165
21·3	13·3	11·2	12·25	8	29·50	1·105
21·54	9·2	8·2	8·7	6	29·64	1·058
21·9	16·8	14·7	15·7	10	29·70	1·157
22·2	15·8	14·1	14·9	10	29·70	1·114
22·54	8·2	7·7	7·95	6	29·64	1·008
22·6	13·0	10·6	11·8	8	29·50	1·180
23·6	15·8	13·7	14·7	10	29 70	1·168
23·7	9·6	8·2	8·9	6	29 60	1·187
24·1	13·1	11·1	12·8	8	29·50	1807
24·14	7 8	6·9	7·35	6	29·64	·907
24·6	15·2	13·9	14·5	10	29·70	1·201
24·8	8.4	7·0	7·7	6	29 60	1·075
25·1	13·1	10·0	11·55	8	29·50	1·228
25 4	14·8	13·5	14·1	10	29·70	1·205
25·49	7·5	6 7	7·1	6	29·64	1·018
26 2	11·6	9 0	10 3	8	29·50	1·143
26·4	14·3	13·2	13·7	10	29·70	1·218
26·99	6·6	6·2	6·4	6	29·64	·971
27·4	7·3	6·6	6 95	6	29 60	1·072
27·7	10·7	8·6	9·65	8	29·50	1·133
27·7	14·6	12·1	13·3	10	29·70	1·240
28·54	6·3	5·9	6·1	6	29 64	·978
28·6	13 6	12·3	12·9	10	29·70	1·242
29·64	5·6	5 2	5·4	6	29·64	·900
29·7	12·9	11·4	12·1	10	29·70	1·210

The first column (on page 59) gives the length of spark in inches, the second gives the corresponding electro-motive force, and the third is the ratio of the latter to the former, and gives the electro-motive force per inch of air at the different distances. If the electro-motive force required had varied directly as the air space, the third column would have been constant.

It is seen, however, that the last column is by no means constant; but the numbers show a very curious and unexpected result—namely, that greater electro-motive force per unit length of air is required to produce a spark at short distances than at long ones; or, if we adopt Faraday's view that the tension exists in every part of the air, they show that air in a thin stratum has greater strength than when it is in a thick one.

It will be seen that my results (pages 61, 62) agree very well with Sir William Thomson's; for he writes, "Greater electro-motive force per unit length of air is required to produce a spark *at short distances than at long.*" For the words in italics I substitute "at low pressures than at high." We may then both write "with a low air 'resistance' than with a high one," or "with few air particles between the points than with many." Sir William Thomson says of his result, "It is difficult even to conjecture an explanation;" I can only say the same of mine.

De La Rue and Müller's Experiments.

On August 23rd, 1877, Messrs. De La Rue and Müller communicated to the Royal Society * a paper, in the early part of which they describe a series of experiments on the "striking distance"—that is, the length of spark obtainable, from batteries of from 1080 to 8040 chloride of silver cells, in various gases, and with terminals of various materials and shapes.

The spark-lengths were measured by means of the discharger A B (fig. 170), which could be placed inside the receiver G G′ of an air-pump, when it was desired to surround it with an atmosphere of any gas.

The discharges took place between the point P and the disc D. Terminals of other shapes could be substituted for this point and disc.

To measure the distance between P and D, the micrometer

* Proc. Roy. Soc., xxvi., 1877, p. 519; Phil. Trans., 1879, vol. clxix. p. 155.

head A was read when a spark was just able to pass, and then the screw-head was turned till P and D just came into contact. The micrometer A being again read, the difference of the two readings gave the "striking distance." The position of contact between P and D was determined by arranging 2 cells, so that their current, which was shown by a detector galvanometer, passed when contact was established. The rod R, which works in a

Fig. 170.

stuffing-box, enabled the screw-head A to be turned without opening the receiver.

The following table gives a summary of the results obtained by Messrs. De La Rue and Müller, for discharges taken between two spherical surfaces.

For purposes of comparison, the numbers given in Sir Wm. Thomson's paper, in another table to that on page 59, have been reduced into volts, and are given in the black figures.

It will be seen that Mr. De La Rue's results agree in the main with Sir Wm. Thomson's, but that the diminution is less rapid.

Plain Numbers, Chloride of Silver Battery.
Black Numbers, Sir Wm. Thomson's Results.

Spark length in inches.		E.M.F. in silver cells.	Difference of potential in volts per centimetre.	
0·00497	**0·00340**	1080	88,060	**80,230**
0·00575	**0·00500**	1200	84,590	**77,000**
0·01434	**0·00600**	2160	61,090	**78,660**
0·01738	**0·00750**	2400	56,010	**67,260**
0·02524	**0·01110**	3240	52,050	**60,220**
0·03000	**0·01610**	3600	48,660	**45,450**
0·03703	**0·02220**	4320	47,320	**43,210**
0·04388	**0·02300**	4800	43,210	**41,870**
0·04925	**0·02710**	5400	44,460	**42,250**
0·05650	**0·03560**	5880	42,210	**40,490**
0·06287	**0·04160**	6440	41,780	**39,630**
0·07025	**0·0522**	6960	40,180	**39,310**
0·07550		7560	40,160	
0·08275		8040	39,420	

Discharge in Different Gases.

On May 17, 1877,* Messrs. De La Rue and Müller stated that the length of spark given by a battery at ordinary atmospheric pressures in the following gases is the longest in the order in which they are enumerated—hydrogen, nitrogen, air, oxygen, carbonic acid—it being nearly twice as long in hydrogen as in air.

The spark does not appear to be dependent on the specific gravity of the gas, but may have some relation to its viscosity.

Vacuum Tubes.

When the pressure of the air is less than about 15 inches of mercury, the appearance of the discharge changes considerably. The whole gas within the tube glows, and if the light be examined with a spectroscope, it will be seen to give the characteristic spectrum of the gas.

* Proc. Roy. Soc., xxvi., 1877, p. 227.

Plate XXXV.—Vacuum Tube fluorescing with Uranium and Sulphate of Quinine.

When the exhaustion is continued by a mercury pump till the pressure is only a very small fraction of a millimetre, the whole tube is filled with a bright light, of which the colour varies with the nature of the residual gas in the tube.

If any fluorescent substances are placed in the tube or surrounding it—if, for instance, a portion of the tube passes through a solution of sulphate of quinine, or part of the glass be coloured with uranium, they will glow with their characteristic colours when illuminated by the electric discharge.

In these "vacuum tubes," as they are called, the electrodes usually consist of platinum or aluminium wires, passed through the glass, which is then fused round them.

Platinum is particularly suitable for this purpose, because its expansion rate is about the same as that of glass, and, therefore, it does not crack out of the glass on cooling. A little opening being left at one side of the tube, the glass is drawn off into a capillary tube and attached to a Sprengel air-pump.

When the exhaustion has been carried as far as required, the capillary tube is heated in a blowpipe flame till it softens, when it is drawn off and so closed, a process which is assisted by the pressure of the external air.

Plate XXXV. represents a tube in the possession of the author. The spiral portion near each end passes through a solution of sulphate of quinine contained in a wider external tube. The green portions are coloured with uranium.

The red shows the natural colour of the discharge in rarefied air. The sulphate of quinine is quite colourless by ordinary daylight, and the uranium very nearly so. The illumination of these portions of the tube by the discharge shows that the latter is peculiarly rich in the ultra violet rays of the spectrum, for it is these which produce fluorescence.*

It is observed that only one of the bulbs at the ends is strongly illuminated. It is the one connected with the negative electrode. On reversing the current, the other is illuminated.

* *See* Lommel, "Optics and Light," ch. xiii. International Scientific Series (Kegan Paul).

Effect of Magnets.

It is found that the discharge in rarefied gas is attracted and repelled by a magnet in the same way as a wire carrying a current subject only to the differences caused by the fact that the wire is rigid and the discharge flexible.

CHAPTER XXXV.

STRIÆ.

It is observed that when the vacuum tube is made somewhat narrow, as, for instance, when it is of the form shown in fig. 171

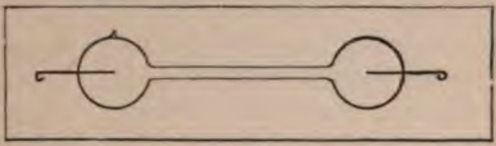


Fig. 171.

that in the narrow part the stream of light is not continuous, but is separated into a number of discs of light.

Under certain circumstances these discs are also observed in larger tubes. They are called "striæ" or stratifications. Their cause is not yet fully understood. Mr. Spottiswoode, Mr. De La Rue, and Mr. Müller have been for some years investigating the subject, and most of what is now known about it is due to their labours, and to those of Mr. Gassiot.

Mr. Spottiswoode's great coil, already described (vol. ii. page 49), was constructed especially for investigations of the striæ, but it has only lately been completed, and we shall have therefore to wait a little longer for the important discoveries which no doubt will be made by means of it.

The following is a summary of the present state of our knowledge on the subject :—

Experiments of Gassiot.

On May 24, 1859, Mr. Gassiot communicated to the Royal Society* the fact that an induction coil is not necessary for the

* Proc. Roy. Soc., vol. x. p. 36.

production of striæ. He found that a "water battery" of 3520 insulated cells would produce a constant succession of sparks between two copper discs ⅛ inch apart. When its poles were connected to the ends of a "carbonic acid vacuum" tube, whose electrodes were some 2 inches apart, a stratified discharge was obtained.

The striæ were also observed when 400 cells of Grove's battery were used.

Carbonic Acid Vacua.

These carbonic acid vacua* were obtained as follows:—A tube, open at both ends, had one end connected to a Sprengel pump and the other to a receiver, containing carbonic acid. Some caustic potash was placed in the tube. When all the air had been replaced by carbonic acid, the end of the tube next the receiver was sealed. The tube was then exhausted as completely as possible, and the second end sealed. On being heated, the caustic potash absorbed nearly the whole of the residual gas, and an extremely perfect vacuum was the result.

Experiments Continued.

On Feb. 6, 1860, Mr. Gassiot made another communication to the Royal Society,† in which he described some experiments made with 512 cells of Daniell's battery, with which he also obtained stratifications. 500 cells of this battery seems about the minimum number which will show this phenomenon, as with 480 Mr. Gassiot was unable to observe it.

When condensers, consisting of from 110 yards to 16 miles of submarine cable, were connected to the tubes, the light in the vacuum tube lasted, after disconnection from the battery, for from a time too short to be measured with the 110 yards, to 1½ seconds with the 16 miles.

Mr. Gassiot finally concludes that the stratified discharge of the induction coil arises from a force acting on highly attenuated but resisting media; and that the same explanation is also applicable to discharges of the voltaic battery in vacua, and that the fact of this discharge having been ascertained to be also

* Carbonic Acid Vacua; Phil. Trans., 1859, page 137, and Bakerian Lecture, Phil. Trans., 1858, p. 1.

† Proc. Roy. Soc., vol. x. p. 393.

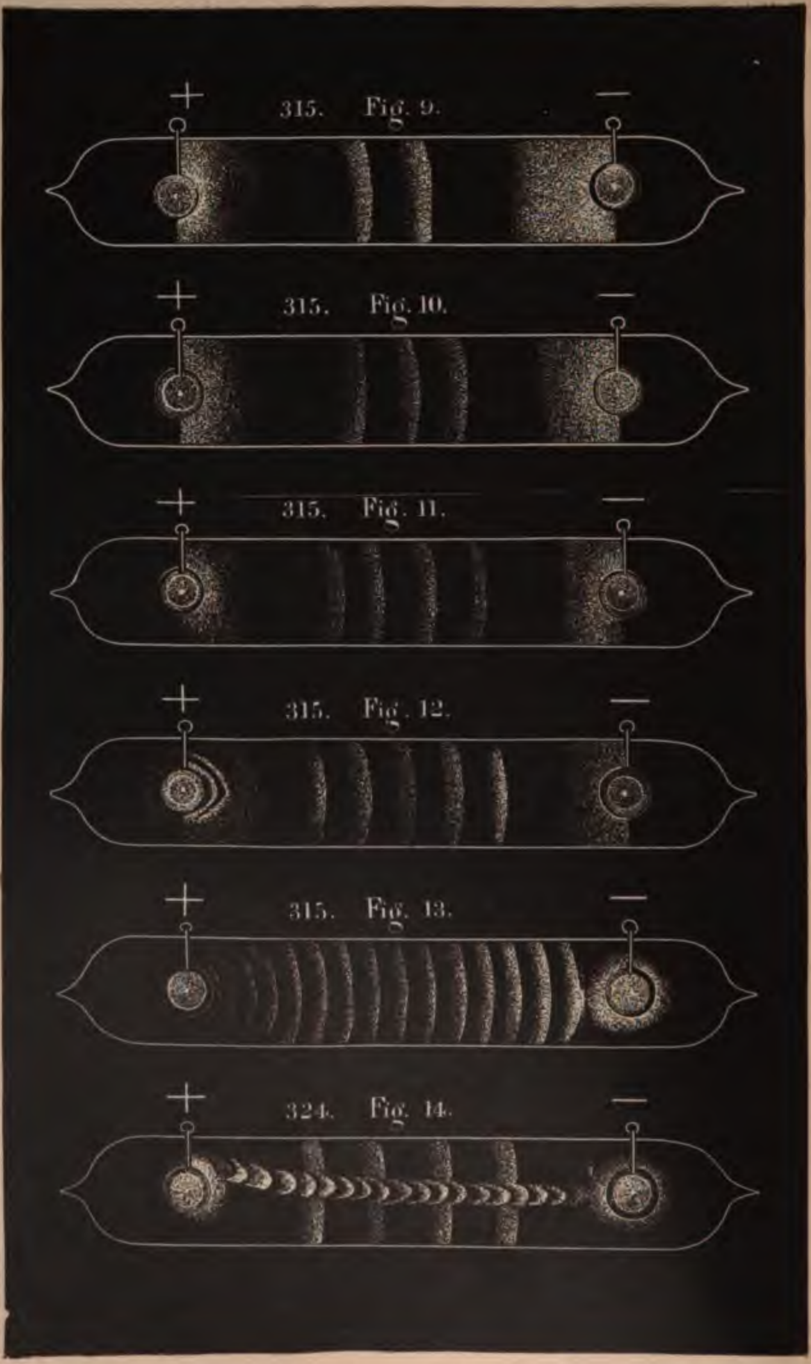


PLATE XXXVII.—GASSIOTT'S VACUUM TUBES.

stratified leads to the conclusion that the ordinary discharge of the voltaic battery is not continuous, but intermittent: that it consists of a series of pulsations of greater or less intensity according to the resistance in the chemical or metallic elements of the battery, or the conducting media through which the discharge passes.*

On December 11th, 1862, Mr. Gassiot announced † that the number and position of the striæ is altered by altering the resistance in circuit.

Plates XXXVI., XXXVII. represent some of the appearances observed in three different tubes, as the potash was heated or cooled, and the resistance in circuit varied.

Mr. Gassiot found that when the pressure in the tube is extremely low, the discharge prefers to pass through even a greater length of air at atmospheric pressure.

At the end of his paper Mr. Gassiot says, "May not the dark bands be the nodes of undulations arising from similar impulses proceeding from positive and negative discharges; or, can the luminous stratifications which we obtain in the closed circuit of the secondary coil of an induction apparatus, and in the circuit of the voltaic battery, be the representation of pulsations which pass along the wire of the former, and through the battery of the latter,—impulses probably generated by the action of the discharge along the wires?"

Experiments of De La Rue, Müller, and Spottiswoode.

On April 8, 1875, a paper was read ‡ by Messrs. De La Rue, Müller, and Spottiswoode, describing experiments with 1080 cells of the chloride of silver battery (vol. i. page 216).

With it several condensers were used: one of them consisted of 350 yards of wire, others of sheets of tinfoil. It was found that tubes which gave no stratifications with the battery, gave them at once when a condenser was added.

It then occurred to the investigators that possibly stratifications accompanied variations in the battery current, and this was found to be the case. The means adopted to ascertain this were as follows:—

* Proc. Roy. Soc., vol. x. p. 404.
† Ibid., vol. xii. p. 329.
‡ Ibid., vol. xxiii. p. 356.

The primary wire of a small induction coil (figs. 172 and 173) (without a contact-breaker) with or without an iron core, was included in the vacuum tube circuit.

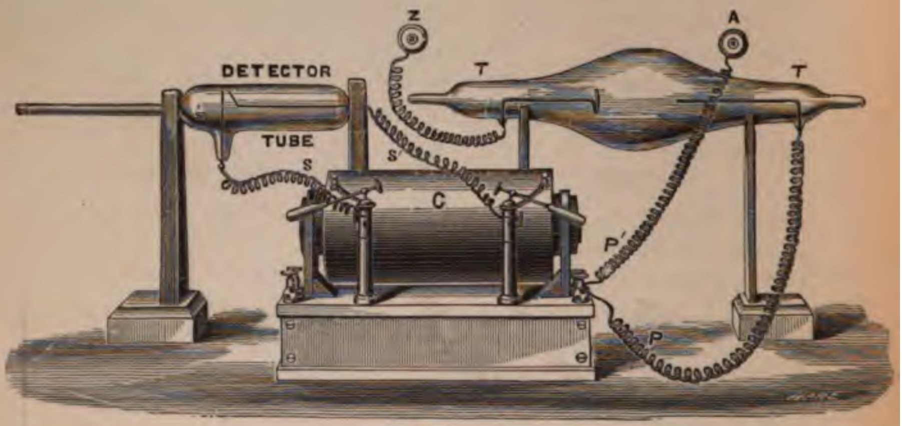


Fig. 172.

Another small vacuum tube, V_2, was attached to the secondary wire. Now, we know that as long as a steady current flows through the primary, there would be no effect on the secondary; but that at every fluctuation a current would be induced in the latter. In the experiments it was found that whenever the discharge in V_1 the first vacuum tube was stratified, the second tube V_2 was lighted up. Fig. 173 shows the arrangements.

It will be understood that the secondary tube was merely used as the most convenient method available, for detecting and estimating the currents of the secondary circuit.

I do not know if the experiment has been tried of omitting the primary vacuum tube from the circuit; but if this were done, I imagine that there would be no illumination of the secondary tube. If this should prove to be the case, it would show, not only that the stratifications are produced by variations of the primary current, but that these variations are themselves produced in the primary tube, probably by some elastic yielding of the attenuated gas, analogous to the vertical oscillations of a weight while being raised by an elastic cord.

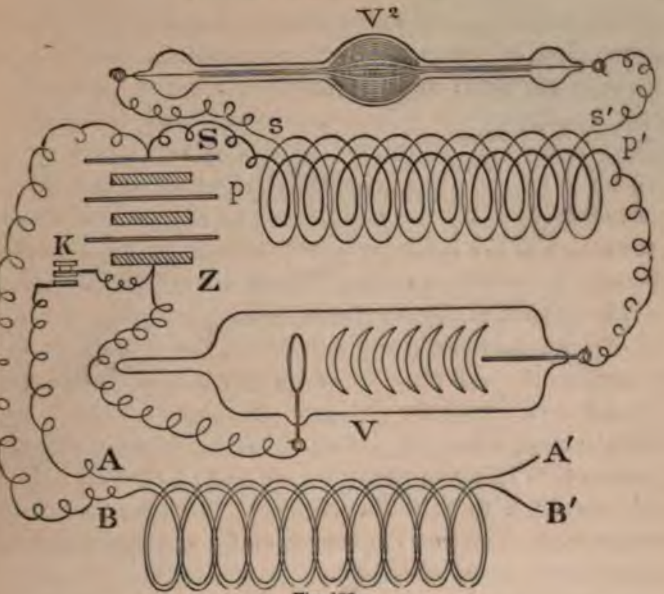


Fig. 173.

SZ is the battery.
V the primary vacuum tube.
pp' the primary coil.
AA' BB' the condenser.
ss' the secondary coil.
V² the secondary vacuum tube.

Experiments of Spottiswoode.

On June 10th, 1875, Mr. Spottiswoode* gave an account of some experiments with the "high break," or, as he now prefers to call it, the "rapid break," described in vol. ii. page 47, figs. 167 and 168. This instrument enabled him, with an induction coil, to obtain effects equally steady and equally under control with those obtained by the batteries.

In this paper Mr. Spottiswoode says :—

"With a contact-breaker of this kind in good action, several phenomena were noticeable; but first and foremost was the fact that, in a large number of tubes (especially hydro-carbons), the striæ, instead of being sharp and flaky in form, irregular in distribution, and fluttering in position, were soft and rounded in outline, equidistant in their intervals, and steady in proportion to the regularity of the contact-breaker. These results are, I think, attributable more to the regularity than to the rapidity of the vibrations. And this view is supported by the fact that, although the contact-breaker may change its note (as occasionally

* Proc. Roy. Soc., vol. xxiii. p. 455.

happens), and in so doing may cause a temporary disturbance in the stratification, yet the new note may produce as steady a set of striæ as the first: and not only so, but frequently there is heard, simultaneously with a pure note from the vibrator, a strident sound, indicating that contacts of two separate periods are being made; and yet, when the strident sound is regular, the striæ are steady. On the other hand, to any sudden alteration in the action of the break (generally implied by an alteration in the sound) there always corresponds an alteration in the striæ.

"It is difficult to describe the extreme delicacy in action of this kind of contact-breaker, or 'high break,' as it may be called. The turning through 2° or 3° of a screw, whose complete revolution raises or lowers the platinum pin through ·025 of an inch, is sufficient to produce or to annihilate the entire phenomenon. A similar turn in a screw forming one foot of the pedestal of the break is enough to adjust or regulate the striæ; and a slight pressure of the finger on the centre of the mahogany stand, apparently rigid, or even on the table on which the contact-breaker stands, will often control their movements.

"The discharges described above are usually (although not always) those produced by breaking contact; but it often happens, and that most frequently when the strident noise is heard, that the current produced by making contact is strong enough to cause a visible discharge. This happens with the ordinary as with the high break; but in the latter case the double current presents the very remarkable peculiarity that the striæ of one current are so arranged as to fit exactly into the intervals of the other; and, further, that any disturbance affecting the column of striæ due to one current affects similarly, with reference to absolute space, that due to the other, so that the double column moves, if at all, as a solid or elastic mass. And this fact is the more remarkable if we consider, as is easily observed in a revolving mirror,* that these currents are alternate, not only in direction, but also in time, and that no one of them is produced until after the complete extinction of its predecessor. And it is also worthy of note that this association of striæ is not destroyed even when the two currents are separated more or less towards opposite sides of the tube by the presence of a magnetic pole. There seems, however, to be a tendency in that case for the striæ of one current

* Vol. ii. page 75.

to advance upon the positions occupied by those of the reverse current, giving the whole column a twisted appearance. But as there is no trace, so far as my observations go, of this association of alternate discharges when produced by the ordinary break, we seem led to the conclusion that a stratified discharge, on ceasing, leaves the gas so distributed as to favour, during a very short interval of time, a similar stratification on the occurrence of another discharge, whether in the same or in the opposite direction. An explanation of the fact that the striæ of alternate discharges occupy alternate and not similar positions is not obvious, and probably demands a better knowledge of the nature of the striæ than we possess at present.

"The column of striæ which usually occupy a large part of the tube from the positive towards the negative terminal have hitherto been described as stationary, except as disturbed by irregularities of the break. The column is, however, frequently susceptible of a general motion or 'flow,' either from or towards the positive pole, say a forward or backward flow. A similar phenomenon was observed by Mr. Gassiot in some tubes with his large battery; but I am not acquainted with the exact circumstances under which it was produced. This flow may be controlled, both in velocity and in direction, by resistance introduced into the circuit, or by placing the tube in a magnetic field. The resistance may be introduced in either the primary or the secondary circuit. For the former arrangement I have successfully employed a set of resistance-coils supplemented by a rheostat. For the secondary current, as well as for the Holtz machine, I have used an instrument devised and constructed by my assistant, Mr. P. Ward, to whose intelligence and skill I am much indebted throughout this investigation, intended for fine adjustment Wherever the resistance be introduced, the following law appears to be established by a great number and variety of experiments, namely, that, the striæ being previously stationary, an increase of resistance produces a forward flow, a decrease of resistance a backward flow. I have generally found that a variation of 3 or 4 ohms, or, under favourable conditions, of 1 or 2 ohms, in the primary current is sufficient to produce this effect. But as an alteration in the current not only affects the discharge directly, but also reacts upon the break, the effect is liable to be masked by these indirect causes. The latter, so far as they are dependent

upon a sudden alteration of the resistance, may be diminished by the use of the rheostat; but when the striæ are sufficiently sensitive to admit the use of this delicate adjustment, some precautions are necessary to insure perfect uniformity of current, so as to avoid disturbances due to uneven contact in the rheostat itself.

"When the striæ are flowing, they preserve their mutual distances, and do not undergo increase or decrease in their numbers. Usually, one or two remain permanently attached to the positive electrode; and as the moving column advances or recedes, the foremost stria diminishes in brilliancy until, after travelling over a distance less than the intervals between the two striæ, it is lost in darkness. The reverse takes place at the rear of the column. As the last stria leaves its position, a new one, at first faint and shadowy, makes its appearance behind, at a distance equal to the common interval of all the others: this new one increases in brilliancy until, when it has reached the position originally occupied by the last stria when the column was at rest, it becomes as bright as the others. The flow may vary very much in velocity; it may be so slow that the appearances and disappearances of the terminal striæ may be watched in all their phases, or it may be so rapid that the separate striæ are no longer distinguishable, and the tube appears as if illuminated with a continuous discharge. In most cases the true character of the discharge and the direction of the flow may be readily distinguished by the aid of a revolving mirror. In some tubes, especially in those whose length is great compared with their diameter, the whole column does not present the same phase of flow; one portion may be at rest while another is flowing, or even two conterminous portions may flow in opposite directions. This is seen also in very wide tubes, in which the striæ appear generally more mobile than in narrow ones. But in all cases these nodes or junction-points of the flow retain their positions under similar conditions of pressure and current; and it therefore seems that, under similar conditions, the column in a given tube always breaks up into similar flow segments.

"These nodes will often disappear under the action of a magnetic pole. Thus if the first segment, measured from the positive terminal, be stationary, and the second be flowing backwards (*i. e.* from — to +), a magnetic pole of suitable strength, placed at the distant end of the latter, will stop its flow, and the

whole column will become stationary throughout. An increase in the strength of the magnet, or a nearer approach of it to the tube, will produce a general forward flow of the column.

The phenomena of the flow, as well as others of not less interest, are capable of being produced with the Holtz machine.

Revolving Mirror.

On May 18, 1876, Mr. Spottiswoode* gave an account of some experiments on the striæ made with a revolving mirror. The break consisted of a plunger working in a mercury and platinum amalgam, and moved by a cam on the axis of the mirror, which insured contact being broken when the spark was in the centre of the field of view.

The axis of rotation of the mirror was vertical, and the light of the tube, which was also vertical, passed through a vertical slit.

Thus, if the mirror were at rest, a continuous discharge would appear in it as a vertical line of light, whose breadth was equal to the breadth of the slit—a striated discharge would appear as a broken vertical line whose bright portions corresponded to the positions of the striæ.

Now let the mirror revolve: a continuous unbroken discharge would present the appearance of a sheet of light; a continuous striated discharge, that of a series of horizontal bars, whose thicknesses were respectively equal to the length of the striæ. An intermittent unbroken discharge would show a series of unbroken vertical lines; and an intermittent striated discharge, a series of broken vertical lines forming horizontal bands, whose thicknesses equalled the length of the striæ. The ratio of the thicknesses of the vertical lines to those of the vertical spaces is of course the ratio of the duration of the discharges to the intervals between successive discharges.

When the distance of the tube from the mirror, and the velocity of rotation is known, the absolute duration of each discharge can be calculated.

Let us now fix our attention on a point of light, and suppose it to move vertically downward.

We should see a diagonal line, whose slope depends on

* Proc. Roy. Soc., vol. xxv. p. 73.

the ratio of the velocity of the point to the velocity of the mirror.*

If the luminosity of the point were continuous, this diagonal line would be continuous; if intermittent, it would be broken.

Thus we see that with the mirror we can measure the duration of the discharges; the interval between each; and the velocity of motion of the striæ—also, if, as often happens, several discontinuous discharges unite to form one apparently continuous, the mirror will resolve it into its constituent elements.

Fig. 174.

Fig. 174 represents the appearance in the mirror of a carbonic acid tube. The commencement of the discharge is at the right

* If a be the angle which this line makes with the horizontal, and v the velocity of the point of light, θ the angular velocity of the mirror, r the distance from axis of mirror to tube, we have: $\tan a = \frac{v}{r\theta}$.

hand (that is, the mirror was turning in the direction opposite to that of the hands of a watch), and the negative terminal is at the top. The positive terminal is a good deal below the picture, so the drawing represents the upper part of the tube during one complete coil discharge. It will be seen that the discharge commences with a perfectly regular set of striæ having a steady downward motion. After a short interval of darkness, a second set are produced, less regular, but somewhat longer lived than the first.

It will be seen that in the upper part of the tube all luminosity soon ceases, but nearer the middle the discharges are repeated again and again.

At the commencement of the region of longer duration we see that each stria moves downward for a short space, when it is extinguished, and its place is taken by another, starting from nearly the same point as the first. Lower down still, the motion of each stria continues longer, and it is no longer formed and destroyed at the same fixed point in the tube. When this tube is viewed by the eye, it shows "flake-like fluttering striæ with a slight tendency to flocculence near the head of the column."

Each of these striæ is, we see, composed of the elements shown in the approximately horizontal bands, each of which is a group of elementary striæ. The curvature of these bands shows the proper motion of the compound striæ: when it is downwards, they are moving from negative to positive; when upwards, in the reverse direction.

Fig. 175, which represents another similar tube, shows the proper motion of the compound striæ more clearly.

Here it is first downward and then upward, but we see from the slope of the lines representing the elementary striæ, that all the proper motion is really from $-$ to $+$, and that the apparent reverse motion of the compound striæ is due to each new elementary stria being formed a little further up than its predecessor.

Fig. 176 represents the discharge of a hydrogen tube of conical form, the diameter of which varied from capillary size to half-inch; the capillary end being at the bottom. The positive terminal is at the top; that is, the current is in the opposite direction to that in figs. 174 and 175. The principal interest of this tube consists in showing the influence of diameter on the velocity of proper motion. The wider the tube, the freer, it seems, are the

striæ to move. We see that this discharge is, though striated, practically continuous.

Fig. 175.

Fig. 176.

The following are the conclusions to which Mr. Spottiswoode thinks "the foregoing experiments seem to lead:" *—

"(1.) The thin flake-like striæ, when sharp and distinct in their appearance, either are short-lived or have very slow proper motion, or both.

"(2.) The apparent irregularity in the distribution of such striæ, during even a single discharge of the coil, is due, not to any actual irregularity in their arrangement, but to their unequal duration, and to the various periods at which they are renewed. These striæ are, in fact, arranged at regular intervals throughout the entire column. The fluttering appearance usually noticeable is occasioned by slight variations in position of the elementary striæ at successive discharges of the coil.

"(3.) The proper motion of the elementary striæ is that which appertains to them during a single discharge of the coil. This appears to be generally directed from the positive towards the negative terminal. Its velocity varies generally within very narrow limits. It is greater the greater the number of coils employed, or the greater the electro-motive force of the current. In some tubes it may be seen to diminish towards the close of the discharge; and even in rare instances alternately to increase and to diminish during a single discharge.

"(4.) Flocculent striæ, such as are usually seen in carbonic-acid tubes, are a compound phenomenon. They are due to a succession of short-lived elementary striæ, which are regularly renewed. The positions at which they are renewed determine the apparent proper motion of the elementary striæ. If they are constantly renewed at the same positions in the tube, the flocculent striæ will appear to have no proper motion and to remain steady. If they are renewed at positions nearer and nearer to the positive terminal, the proper motion will be the same as that of the elementary striæ; if they are renewed at positions further and further from the positive terminal, the proper motion will be reversed.

"(5.) The velocity of proper motion varies, other circumstances being the same, with the diameter of the tube. This was notably exemplified in the conical tube. In tubes constructed for spectrum analysis, the capillary part shows very slight, while the more open parts often show considerable, proper motion.

* Proc. Roy. Soc., vol. xxv. p. 81.

"(6.) Speaking generally, the discharge lasts longer in narrow than in wide tubes. In spectrum tubes the capillary part gives in the mirror an image extending far beyond that due to the wider parts.

"(7.) The coil discharge appears, in the earlier part of its development at least, to be subject to great fluctuations in extent. In all cases there is a strong outburst at first. This, although sometimes appearing as a bright line, is always, I believe, really stratified. Immediately after this there follows a very rapid shortening of the column. The extent of this shortening varies with circumstances; but when, as is often the case, it reaches far down towards the positive terminal, a corresponding diminution of intensity is perceptible in the negative glow. The column of striæ, after rising again, is often subject to similar fluctuations. These, which are sometimes four or five in number, are successively of less and less extent, and reach only a short distance down the column of striæ. The rifts due to these fluctuations then disappear, and the striæ either continue without interruption, or follow, broken at irregular intervals, until the close of the discharge.

"(8.) The effect of the proper motion, taken by itself, is to shorten the column of striæ. But, as we have seen, the striæ are in many cases renewed from time to time. In regard to this point, the head of the column presents the most instructive features. After the cessation of these rifts, the general appearance of the field is that of a series of diagonal lines commencing at successive points which form the bounding limit of the column at successive instants of time. If the points are situated in a horizontal line, the striæ are renewed at regular intervals at the same place; and the length of the column is maintained by a periodic renewal of striæ, a new one appearing at the head of the column as soon as its predecessor has passed over one dark interval. If the boundary of the illuminated field rises, the length of the column increases; if it descends, the column shortens. In every case, however, the growth of the column takes place by regular and successive steps, and not irregularly. The intervals of the new striæ from one another and from the old ones are the same as those of the old ones from one another.

"(9.) The principal influence of a change in the electro-motive force appears to consist in altering the velocity of proper motion.

A change in the amount of battery-surface exposed produces a corresponding change in the duration of the entire discharge, as well as apparently in the development of some of the minor details of the striæ.

"(10.) When the proper motion of the elementary striæ exceeds a certain amount, the striæ appear to the eye to be blended into one solid column of light, and all trace of stratification is lost. When this is the case, the mirror will often disentangle the individual striæ. But there are, as might well be expected, cases in which even the mirror is of no avail, but in which we may still suppose that stratification exists. A variety of experiments have led me to think that the separation of the discharge into two parts, viz., the column of light extending from the positive terminal, and the glow around the negative, with a dark space intervening, may be a test of stratified discharge; but I cannot affirm anything certainly on this point."

Experiments of De La Rue and Müller.

On Aug. 23rd, 1877, Messrs. Warren De La Rue and Hugo W. Müller communicated a paper to the Royal Society "On the Electric Discharge of the Chloride of Silver Battery," part I.* Part II.† was communicated April 10, 1878. In the first part of this paper they give an account of the construction of the great chloride of silver battery,‡ which now (1879) consists of 8040 cells. The first experiments with it were devoted to seeing whether the discharge, in highly-exhausted tubes, is of the nature of a true current, or whether it was disruptive like that through air at ordinary pressures. For this purpose they arranged that the discharge of 2400 cells should pass through a circuit consisting of a vacuum tube, and a large resistance. The resistance was then varied, so that the strength of the current varied in the proportion of from 1 to 135, but it was found that the difference of potential at the ends of the tube remained almost absolutely constant. Now, by Ohm's law, the potential along a conductor falls regularly along the resistance, and, therefore, if the vacuum tube had been an ordinary conductor, there would have been a uniform fall of potential along the whole circuit,

* Phil. Trans., part i. vol. clxix. p. 55.
† Ibid., part i. vol. clxix. p. 155.
‡ See vol. i. p. 216.

consisting of tube A B and resistance B C (fig. 177); and the line L M C would have been straight from L to C; as it was, however, it was found that however much the slope of the part M C

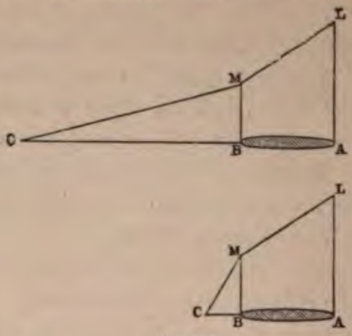


Fig. 177.

varied, that of L M representing the fall of potential along the tube remained constant.

This shows that the discharge is not a case of true conduction, but that even at the lowest pressure it is *disruptive.*

METHOD OF EXHAUSTION.

We next come to the method of exhausting the tubes, so as to reproduce different phases of the phenomena at will. When tubes were exhausted and sealed once for all, it was found that, after a few discharges had passed, their character changed, and it was impossible to restore them to their original state. The tubes were therefore arranged so that the discharges could be passed while the exhaustion was in progress. When any particular phenomenon was observed, the pressure was noted, and on again adjusting to that pressure, the phenomenon could be reproduced.

Plate XXXVIII. is a picture of Mr. De La Rue's air-pumps, &c. The arrangement comprises three means of exhaustion, which are successively employed as the vacuum becomes more perfect.

The first is an Alvergniat high-pressure water *trompe* in connection with the high-pressure water-main of the West Middlesex Water Company, the head of water being 106 feet; it produces a vacuum to within half an inch (0·47 in. = 12 millims.) of the height of the barometer.

The pipe leading to it is so marked in the drawing; it is attached, through a cock to a four-way junction piece F, provided with three more cocks, communicating one to one end

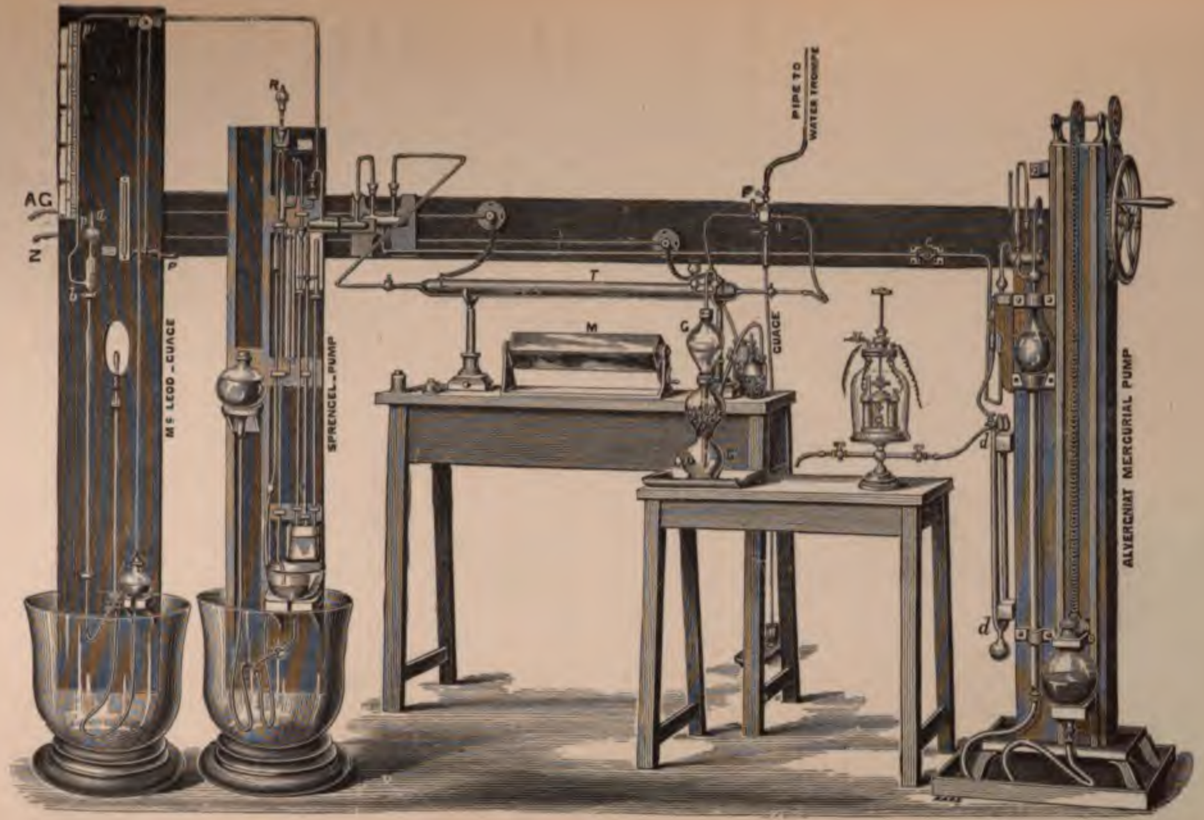


PLATE XXXVIII.—DE LA RUE'S AIR-PUMPS, ETC.

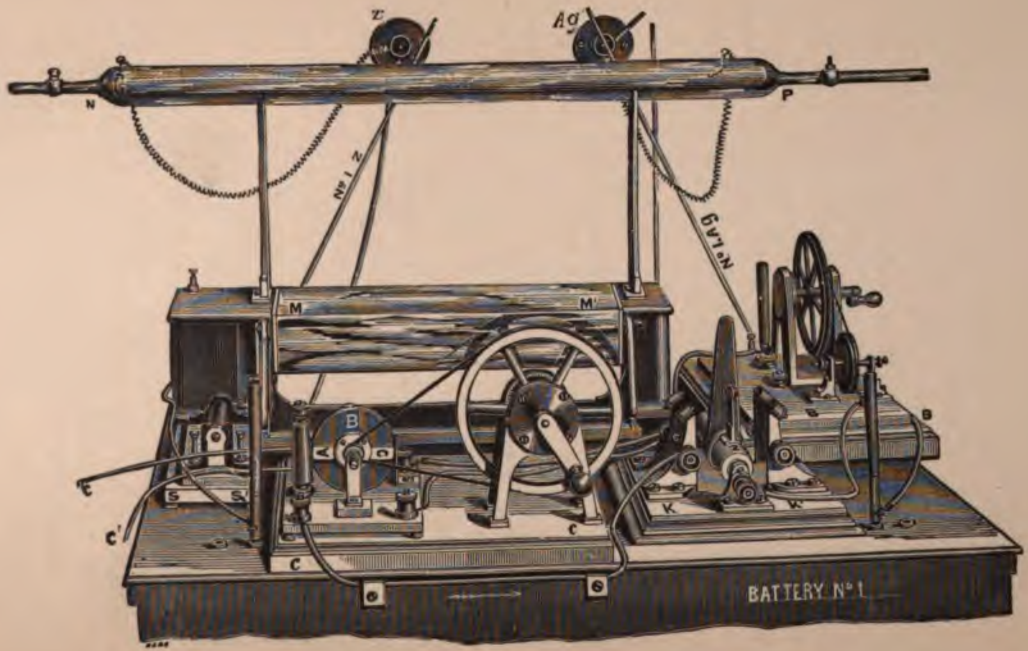


Plate XXXIX.—De la Rue's apparatus.

of the tube T, one to the last drying bottle of the gas generator G G, and one to a mercurial gauge. The other end of the vacuum tube T communicates by means of a Y piece to both an Alvergniat mercurial pump on the right of the figure, and a Sprengel pump on the left. After the *trompe* has done its work, the Alvergniat is used for rapid exhaustion, and then shut off by means of the glass cock C, leaving the exhaustion to be completed by the Sprengel; the authors have obtained by the *pumps alone* in tubes 32 inches long, and 2 inches in diameter, vacua of only 0·002 millim. pressure, equal to 2·6 millionths of an atmosphere—a vacuum so perfect, that the current of 8040 cells would not pass. The apparatus is in connection with a M'Leod gauge,* by means of which pressures to 0·00005 millim. can be determined. Besides this gauge, the Sprengel and Alvergniat pumps have their own gauges, which read to a millimetre.

ARRANGEMENT OF THE APPARATUS.

Plate XXXIX. shows the general arrangement of the apparatus. AC is a rapid commutator for sending currents alternately in the two directions. K is a reversing key specially constructed to give good insulation with the immense electro-motive forces employed. When the handle is vertical, as shown, no current passes. Moving the handle to right or left sends the current in the two directions respectively through the tube. BB is a wheel-break for producing rapid intermittence. Z and Ag. are the zinc and silver terminals of the battery respectively.

M (Plates XXXVIII., XXXIX.) is a rotating mirror, consisting of a four-sided prism, mounted on a horizontal axis, and provided with a multiplying wheel; on each face of the prism is fastened a piece of looking-glass. The reflection of the tube in the mirror enables one to examine whether an apparently nebulous discharge consists really of striæ, also whether and in what direction there is a flow of striæ which may appear quite steady to the eye.

The observations are facilitated by covering the tube with a half-cylinder of cardboard, having a slit in the direction of its axis about $\frac{1}{10}$ inch wide. R (Plate XXXVIII.) is a radiometer attached to the Sprengel; *d d* a drying tube containing sticks of potash, used when gas is introduced from a reservoir through the Alvergniat.

* (Phil. Mag., Aug. 1874.) When the mercury cistern is raised, a portion of gas at the same pressure as that in the tube is shut off at *b*, and com-

In order to save writing decimals, the pressures are usually expressed in millionths of an atmosphere written **M**.

1 millim. of mercury = 1315·789 **M**.
1 **M** = ·00076 millims.

In the present experiments the pressures varied from about 20,000 **M** to 3 **M**; with less than about 3 **M** the current of 11,000 cells would not pass in tube 129.

The exhaustion of an ordinary vacuum tube, arranged to give the best luminous effects, is from 2 to 4 millims., say

from 2,000 **M** to 5,000 **M**.

The battery power used varied from 3,000 to 11,000 cells.

Tubes whose length varied from 6 or 7 inches to 3 feet were used, and by means of the pumps they could be filled with different gases as described.

The most marvellous and beautiful striæ were observed in all manner of strange shapes.

It would be impossible in the space at our disposal to give detailed accounts of the innumerable separate phenomena described in the paper. The student is recommended to study them in the "Philosophical Transactions." We have, however, reproduced some of the pictures of the more striking forms. Tube 129 (fig. 178) was 32 inches long, and 1·6 inch in diameter. Its terminals were a ring and a wire of aluminium. It was charged with hydrogen.

Plates XL., XLI., XLII. are sketches of some of the phenomena observed with this tube in different stages of exhaustion, and with different battery powers.

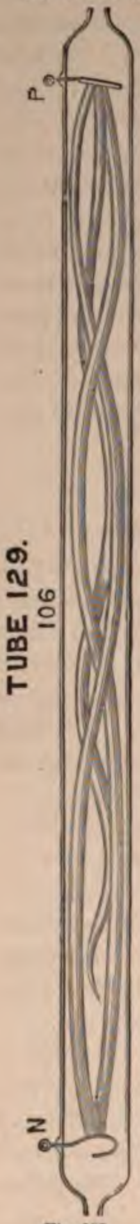


Fig. 178.

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pressed in the small graduated chamber, a, at the top of the bulb to different degrees in one gauge, from $\frac{1}{19{\cdot}83}$ to $\frac{1}{13{\cdot}5}$, according as the gas is less or more rarefied; the mercury at the same time rises in the pressure column p, and its height affords the means of determining the pressure of the gas in the tube. Tables have been prepared to give the value of the reading by inspection.

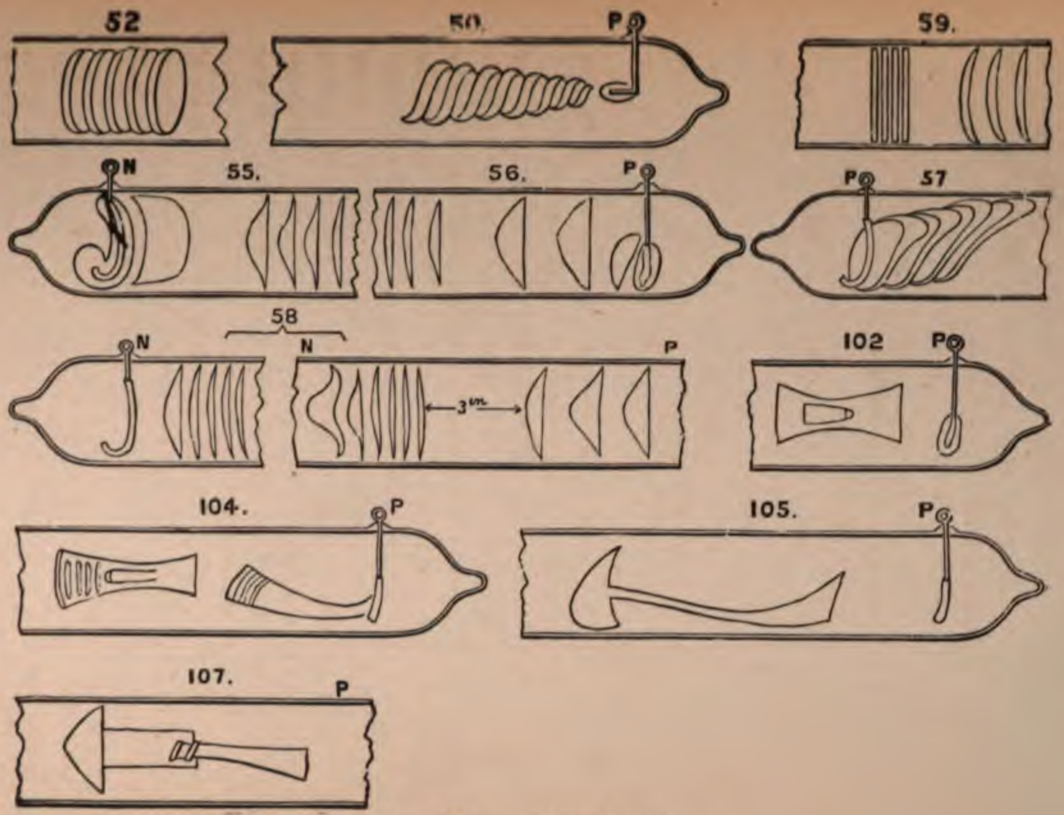


PLATE XL.—DE LA RUE'S STRIÆ.

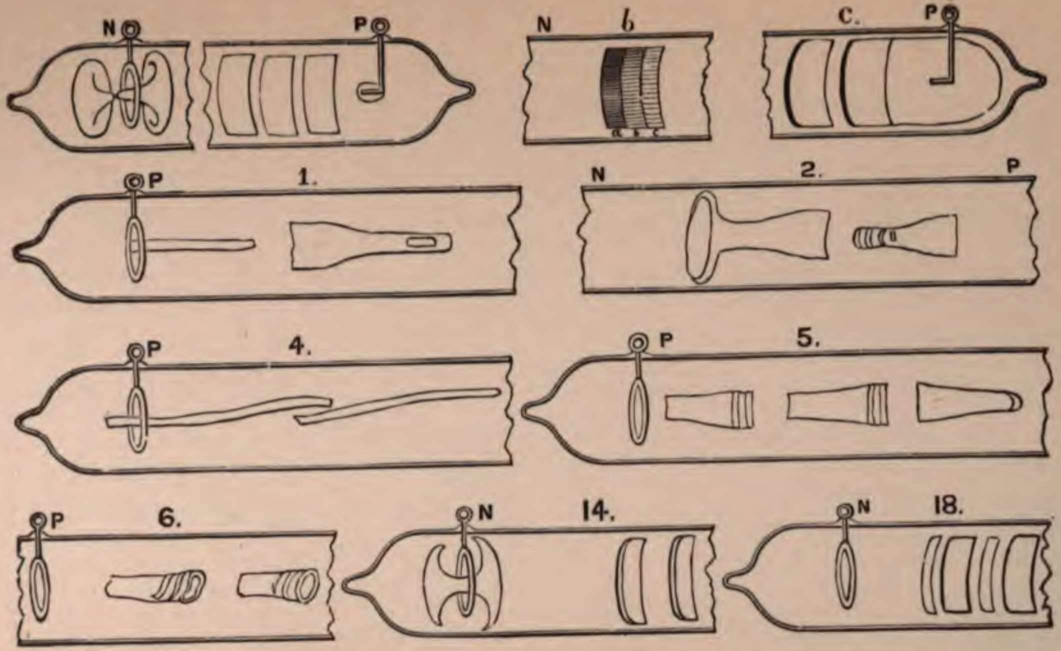


Plate XLI.—De la Rue's Striæ.

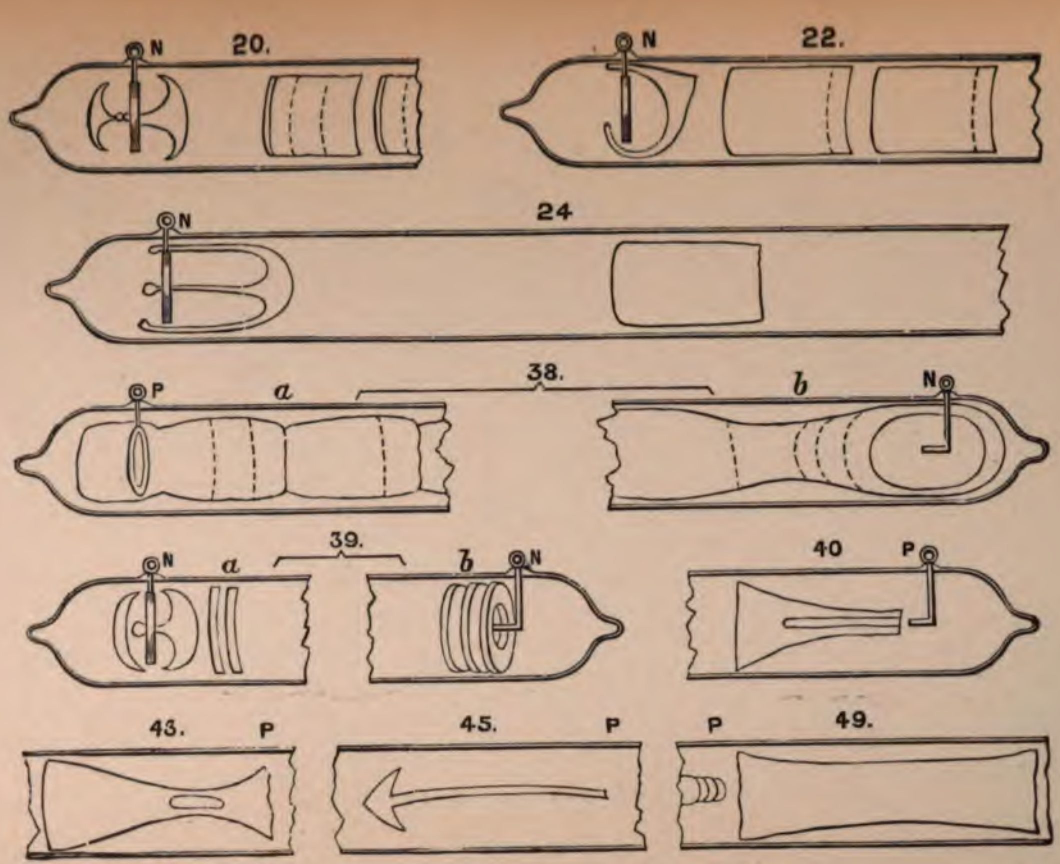


PLATE XLII.—DE LA RUE'S STRIÆ.

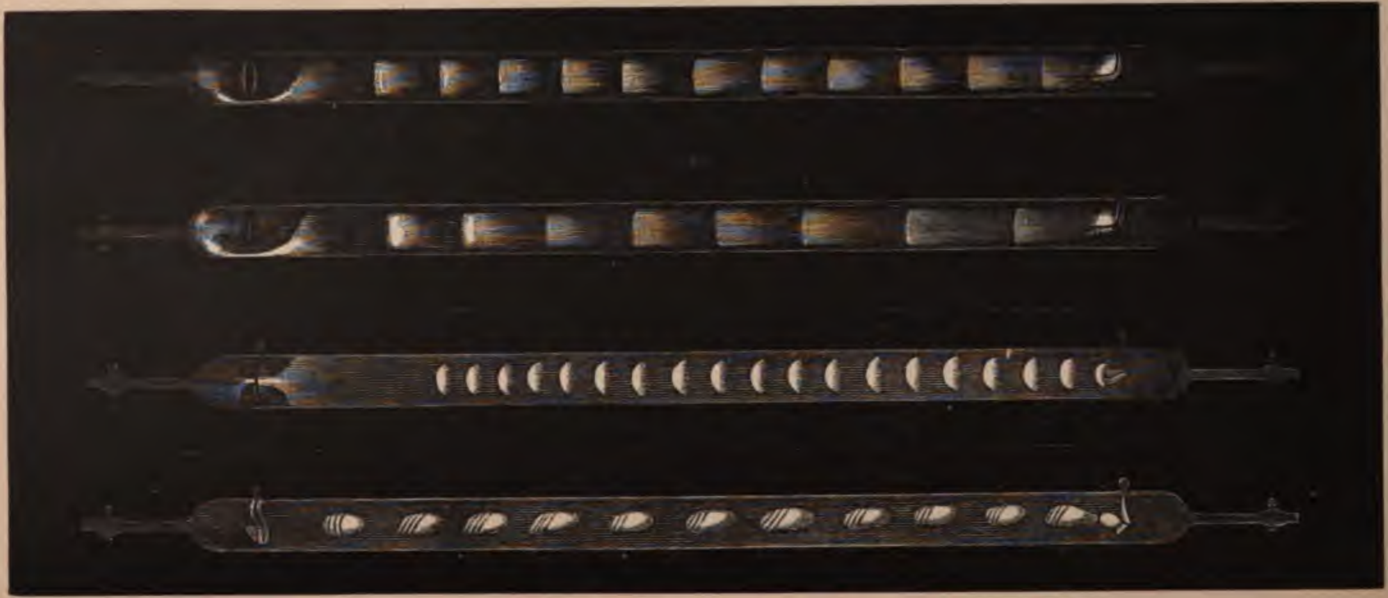


Plate XLIII.—De la Rue's Striæ.

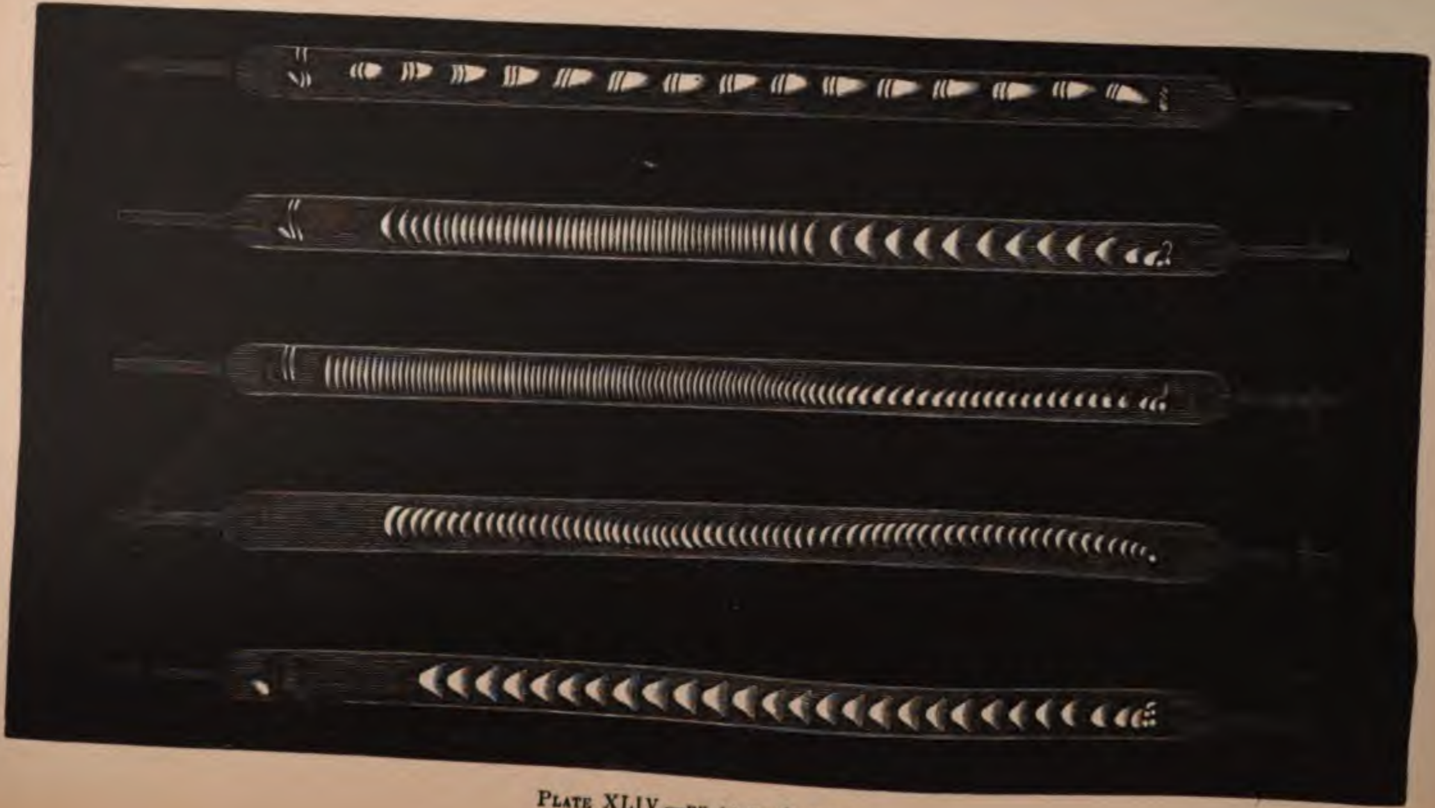


PLATE XLIV.—DE LA RUE'S STRIÆ.

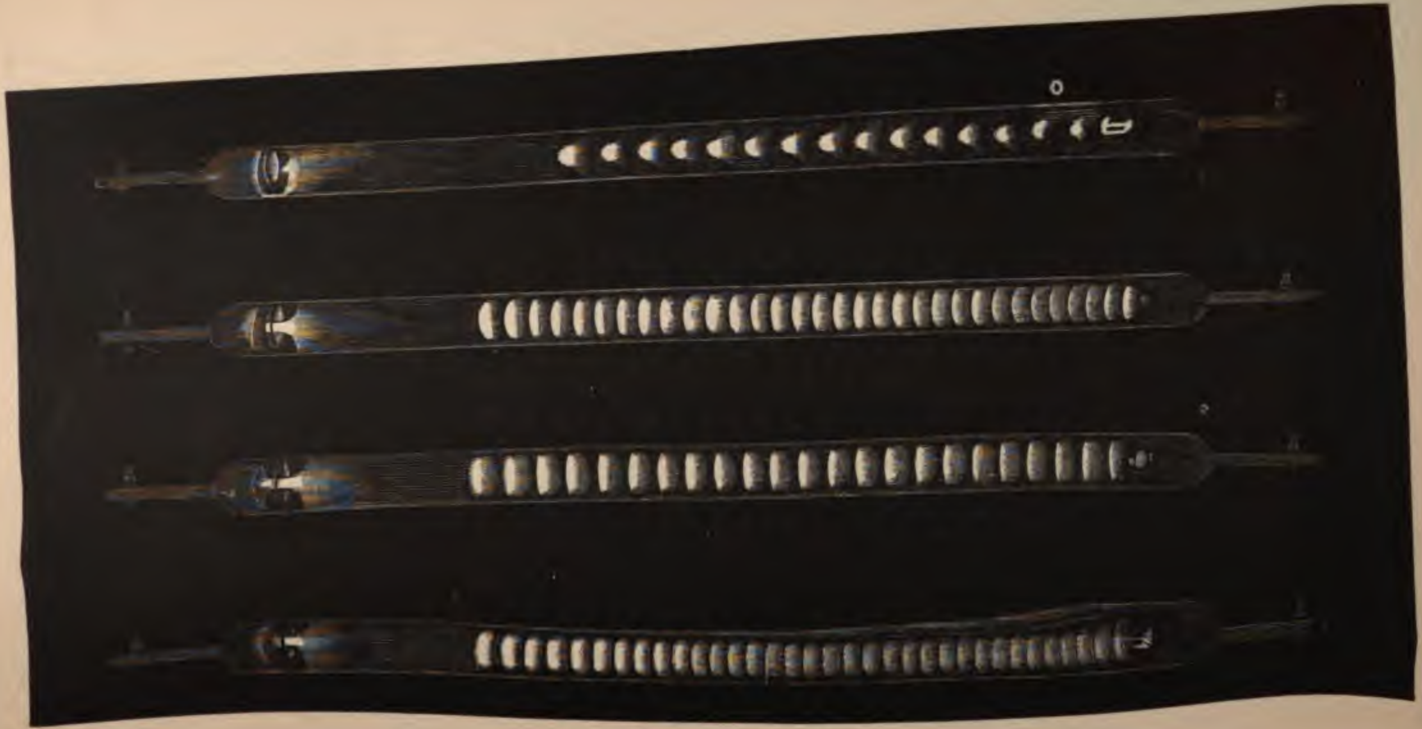


Plate XLV.—De la Rue's Striæ.

These curious-shaped figures are all masses of light of various colours; "luminous entities" the authors of the paper call them. Sometimes they are in motion, sometimes at rest.

Plates XLIII., XLIV., XLV. are engravings from photographs of the discharges, taken actually from the tubes.

Mr. De La Rue gives histories of all his tubes, and describes all the phases as they occur. He and Mr. Müller thus sum up the results of all their experiments:—

"1. The discharge in a vacuum tube does not differ essentially from that in air and other gases at ordinary atmospheric pressures; it cannot be considered as a current in the ordinary acceptation of the term, but must be of the nature of a disruptive discharge, the molecules of the gas acting as carriers of electrification. The gases in all probability receive impulses in two directions at right angles to each other, that from the negative being the more continuous of the two.* Metal is frequently carried from the terminals, and is deposited on the inside of the tube, so as to leave a permanent record of the spaces between the strata.

"2. As the exhaustion proceeds, the potential necessary to cause a current to pass, diminishes up to a certain point, whence it again increases, and the strata thicken and diminish in number, until a point is reached at which, notwithstanding the high electro-motive force available, no discharge through the residual gas can be detected.† Thus when one pole of a battery of 8040 cells was led to one of the terminals of tube 143, which has a radiometer attached to it, the other terminal of the tube, distant only 0·1 inch, being connected through a sensitive Thomson galvanometer to the other pole of the battery (earth), the current observed was not greater than that which was found to be due to conduction over and through the glass. Although no current passed, the leading wires, acting inductively, stopped the motion of the radiometer, as has been observed by Mr. Justice Grove.

"3. All strata have their origin at the positive pole. Thus in

* De La Rue and Müller, Phil. Trans., 1878, vol. clxix. pp. 90 and 118.

† From observations with pressure varying from 6·4 to 145·1 millims. Wiedemann and Ruhemann conclude that the accumulation requisite to produce discharge increases with the pressure at first quickly, then more slowly; towards the upper limit of their experiments it becomes nearly proportional to the pressures. See also vol. ii. pp. 55 to 64 above.

a given tube with a certain gas, there is produced at a certain pressure, in the first instance, only one luminosity, which forms on the positive terminal, then as the exhaustion is gradually carried further it detaches itself, moving towards the negative, and being followed by other luminosities, which gradually increase in number up to a certain point.

"4. With the same potential the phenomena vary irregularly with the amount of current. Sometimes, as the current is increased, the number of strata in certain tubes increases, and as it is diminished, their number decreases; but with other tubes, the number of strata frequently increases with diminution of current. If the source of the current is a charged condenser, the flow being from one of its plates, through resistances and the tube, to the other, then, as the potential of the condenser falls, and the current diminishes, the number of strata alters; if the strata diminish in number with the fall of potential, then the stratum nearest the positive wire disappears on it, the next then follows and disappears, and so on with the others; if, on the other hand, the charge of the condenser is very gradually increased, the strata pour in, one after the other, in the most steady and beautiful manner from the positive.

"5. A change of current frequently produces an entire change in the colour of the strata.

"For example, in a hydrogen tube from a cobalt blue to a pink.

"It also changes the spectrum of the strata; moreover, the spectra of the illuminated terminals and the strata differ.

"6. If the discharge is irregular and the strata indistinct, an alteration of the amount of current makes the strata distinct and steady. Most frequently a point of steadiness is produced by the careful introduction of external resistance; subsequently the introduction of more resistance produces a new phase of unsteadiness, and still more resistance another phase of steady and distinct stratification.

"7. The greatest heat is in the vicinity of the strata. This can be best observed when the tube contains either only one stratum, or a small number separated by a broad interval. There is reason to believe that even in the dark discharge there may be strata; for we have found a development of heat in the middle of a tube in which there was no illumination except on the terminals.

"8. Even when strata are to all appearance perfectly steady, a pulsation can be detected in the current; but it is not proved that the strata depend upon intermittence.

"9. There is no current from a battery through a tube divided by a glass division into two chambers, and the tube can only be illuminated by alternating charges.

"10. In the same tube, and with the same gas, a very great variety of phenomena can be produced by varying the pressure and the current. The luminosities and strata, in their various forms, can be reproduced in the same tube, or in others having similar dimensions.

"11. At the same pressure and with the same current, the diameter of the tube affects the character and closeness of stratification.

"We defer for the present the suggestion of any theory to account for stratification, in the hope of being able to confirm experimentally certain views which we entertain as to the cause of this phenomenon.

CHAPTER XXXVI.

ON THE SENSITIVE STATE OF DISCHARGES THROUGH RAREFIED GASES.

On April 2, 1879, Mr. William Spottiswoode and Mr. J. F. Moulton communicated to the Royal Society a paper "On the Sensitive State of Electrical Discharge through Rarefied Gases."*

Definition and Description.

It has frequently been remarked that the luminous column produced by electric discharges in vacuum tubes occasionally displays great sensitiveness on the approach of a finger or other conductor to the tube. The exact effect of such approach varies considerably with the circumstances of the discharge. In many instances the luminous column is repelled; in others, and especially when the finger is brought into actual contact, the column is severed; and in the latter case, in addition to the luminosity previously present, there often appears proceeding from the interior of the tube, at the point where the finger rests, the blue haze which usually characterizes the negative end of a discharge. In some cases the discharge is so powerfully affected that the well-known green or blue fluorescence appears on the side of the tube opposite to the point touched.

The degree of sensitiveness varies between wide limits. Discharges frequently occur in which close observation is necessary to detect any trace of it, while others may be produced so sensitive that the magnetic action of a powerful electro-magnet is comparable to the action which is due to it as a conductor. The condition in question does not appear to be confined to any particular gaseous medium or to any special form of tube; and it is

* Phil. Trans., 1879, page 165.

in fact probable that in almost any tube sensitiveness may be produced by adopting suitable precautions. This state of sensitiveness may be exhibited by stratified discharges, but it is more commonly associated with those which show no clear traces of stratification. It is not, however, universally present in either kind of discharge.

The present paper is devoted to an examination of the causes which produce this state, and the laws which regulate it.

Due to Intermittence.

The first result which the authors arrived at was that

The Sensitive state is due to a Periodic Intermittence of considerable rapidity and regularity, the quantity of Electricity in each individual Discharge being sufficiently small to permit the Discharge to be instantaneous.

The simplest way to produce intermittence is to illuminate the tube by means of a Holtz machine or other constant source of electricity, and to interpose a small air-spark in one of the wires leading from the machine to the tube (fig. 179).

Fig. 179.

As soon as the air-spark is made to intervene, the discharge in the tube becomes sensitive; and this sensitiveness may in general be increased by increasing the length of the air-spark, until the discharge becomes visibly intermittent, so as no longer to appear to the eye as a steady continuous discharge. Although this is by no means the only way in which the sensitive discharge can be produced, it is the one which is the most generally convenient for the purposes of experiment; and it may on that account be regarded as the typical mode of production.

Indications of the sensitive state can also be produced by the use of an induction coil in connection with a large condenser.

If the discharge be allowed to pass through the tube while the coil is at work, a certain amount of sensitiveness will usually be visible. But if the coil be stopped and the current allowed to flow from the condenser through the tube without disturbance from the entrance of the coil discharges, the discharge will in general be found to have lost all its sensitiveness.

Again, certain tubes appear to render the discharge from a continuous source sensitive without the necessity of artificially producing intermittence in the current.

Again, a sensitive discharge may be produced by connecting one terminal of the machine with one terminal of the exhausted tube, and the other terminal of the machine with the outside of the tube (fig. 180). If the current be then permitted to pass

Fig. 180.

between the terminals of the machine by leaping a considerable distance (say half an inch) in air, so that the discharges in the tube are caused partly by conduction from one terminal of the machine and partly by induction due to the rapid alternations of high and low tension in the wire from the other terminal of the machine to the outside of the tube, the resulting discharge will be found to be sensitive.

Again, rapid intermittence and sensitiveness in what would otherwise be a continuous discharge may be produced by the use of a "wheel-break" (vol. ii. page 47). If the wheel-break be interposed in the circuit of a Holtz machine when producing a luminous discharge in a vacuum tube, and the break be worked at a considerable speed, so as to cause the current to be interrupted some 400 to 2000 times per second, the discharge becomes highly sensitive. The wheel-break is used as a shunt, viz., so as to divert from the tube the current given by the machine during the time which the platinum spring rests upon the metallic portion of the wheel. In this way the current is never actually broken, and one great advantage of this arrangement is that it

simply produces intermittence in the discharge in the tube without interfering with it in any other way.

Another method of producing the sensitive state is by the use of a "Rapid Break."* If such an instrument be used with an

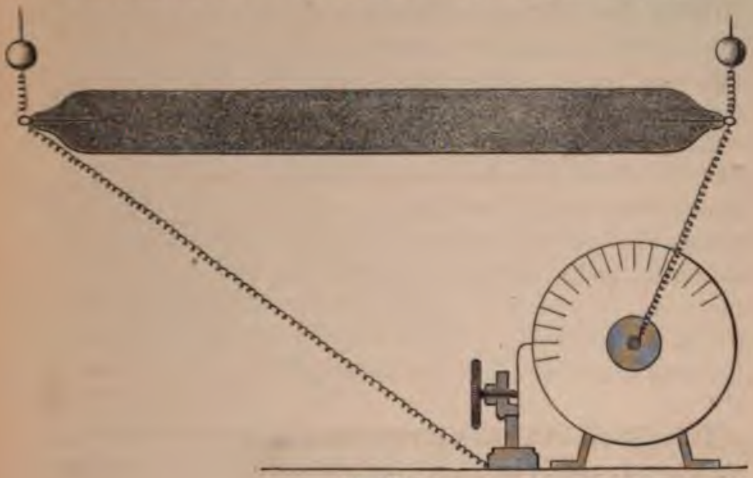


Fig. 181.

induction coil, the discharge, though often beautifully stratified, is intensely sensitive. The lowest limit of rapidity with which the authors have produced *stratified* sensitive discharges in this way is 240 breaks per second.

No Sensitiveness without Intermittence.

The authors examined a great many sensitive discharges by means of a telephone and a revolving mirror, and they found that in every case intermittence was necessary to sensitiveness.

The revolving mirror was used in the manner described in vol. ii. page 75. If the body of the tube containing the discharge be hidden by an opaque screen which contains a narrow longitudinal slit, and the image of this slit be observed in a rapidly revolving plane mirror, a series of bright and black bands appear whenever the discharge is sensitive, showing that there are intervals between the luminous discharges during which the tube is dark. If the ordinary non-sensitive discharge be observed in a similar way, there are no such dark bands, and no available speed of the

* Vol. ii. page 47.

mirror suffices to show any break in the uniformity of the luminous image of the slit. The occurrence of these dark bands shows conclusively that the discharge in which they appear is intermittent and discontinuous.

When the telephone is inserted in circuit with a non-sensitive tube, there is sometimes a rushing sound, but in a very large number of cases there is absolute silence. But as soon as the discharge becomes sensitive, the silence is broken by a shrill sound; or if the rushing sound of which we have spoken previously existed, there is a sudden change in the character of the sound, which usually becomes musical. The pitch of the note is always high, and naturally varies with the circumstances of the discharge, and it is therefore probable that, in cases where it is not heard, its pitch is too high, and the note itself is possibly too feeble, for audibility. When the air-spark is again abolished, the note ceases, or gives way to the rushing sound mentioned above.

It is observed that all the methods of producing the sensitive state agree not only in the intermittent character of the discharge, but also in the shortness of duration of the individual discharges themselves, and this has induced the authors to regard *brevity of duration* as much an essential feature of the individual discharges that produce the sensitive state as rapidity or regularity of interval between these discharges.

The latter characteristics are of more importance for maintaining the persistence of the sensitive state during a finite interval of time than for actually producing it, since careful experiments fail to show any inferior limit of rapidity of the periodicity necessary to produce such a discharge. In truth, there is no impossibility in producing by a single flash a discharge having the characteristics of sensibility. If a charged Leyden jar* be employed with a suitable tube, the instantaneous discharge that passes through the tube on the jar being connected with it will show all the symptoms of sensitiveness during its passage through the tube.

The authors next state that

The effect produced by the approach of a conductor to a sensitive discharge is directly due to the relief given by its presence to the instantaneous electric tension within and around the tube

* Proc. Roy. Soc., xxvi., 1877, p. 90.

caused by the individual discharges in their passage through the tube.

In the case of the sensitive or interrupted discharge, we have seen that there are separate pulses of electricity passing between the terminals.

It is not improbable that each of these pulses leaves the positive terminal in the form of free electricity.

If it does so, it will exercise induction in every direction, and cause a "state of strain" on the glass and in the space beyond.

As the glass is a non-conductor, this state of strain continues; but the instant a conductor is brought near, the state of strain is *relieved*, and a complete redistribution of the electricity outside the tube takes place. The state of the electric field in the neighbourhood of the conductor will then be different to that at any other part of the tube; and this will in its turn react upon the discharge or upon the gaseous matter which exists within the tube.

In order to show that the phenomena of sensitiveness are primarily due to the redistribution of the induced electricity and relief of the external strain, it is only necessary to observe that a non-conductor, however highly charged, does not affect the sensitive discharge. Nor will a conductor of small size, in contact with the tube (such as a piece of tinfoil), affect the discharge so long as it is insulated. But if the tinfoil be connected to earth, or to a distant conducting body, an effect on the sensitive discharge is at once seen.

A consideration of these experimental facts leads the authors to the following conclusions :—

(1) That the effect is due to a redistribution of electricity in the conductor; and

(2) That such effect is periodic.

If a continuous electric state in the external body were the necessary condition, the observed effect could be produced by charged non-conductors. But as this is not the case, we must look to the facility of change in electric state afforded by conductors for an explanation of their effect on the sensitive discharge. This conclusion is supported by the fact previously stated, that a small piece of tinfoil placed upon the tube produces no effect so long as it is insulated. Such a piece of tinfoil would give but little scope for redistribution of electricity—at all events,

in such a way as to affect the space around it. But if it be connected metallically with a distant conducting body, so that positive or negative electricity can be driven from it to a sensible distance from the tube, the case is different; and, if this be done, it is at once found to affect the sensitive discharge.

If then the effect on the sensitive discharge is caused by the facility for a redistribution of electricity within the conductor, it follows that there must be a varying electric action upon it from the discharge in the tube. And that such is the case may be shown by connecting a ring, or segment of a ring, of tinfoil, placed on or near the glass (fig. 182), with the earth,

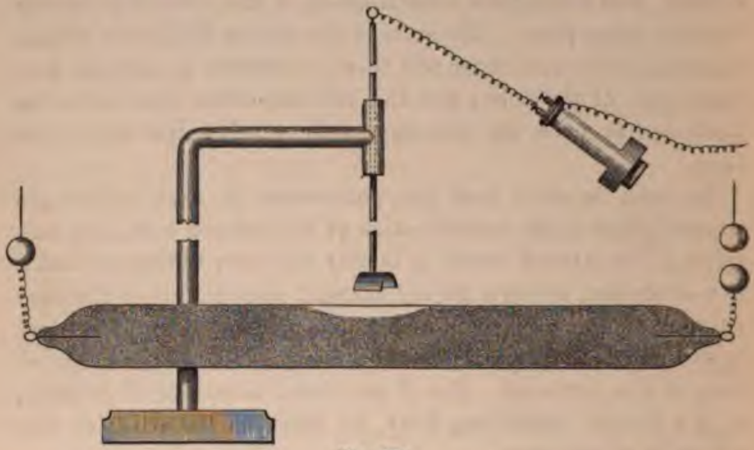


Fig. 182.

and interposing a telephone in the circuit between the tinfoil and the earth. As soon as the current becomes interrupted by an air-spark, a sound is heard in the telephone corresponding with the sound of the air-spark causing the intermittence. This shows conclusively that at each pulsation there is an electrical redistribution within the system composed of the earth, the wire, and the tinfoil. And as this continues indefinitely, without producing any charge upon the tinfoil, it is clear that there must, during the complete period of each pulsation, be a flow of one kind of electricity from the tinfoil, followed by its return, or by a similar flow of the opposite kind of electricity from the tinfoil.

The authors go on to describe experiments to show that—

(1) The effects are due to electro-static, and not to electro-magnetic, induction.

(2) That the "relief effect" is independent of the potential of the conductor causing the relief.

That is, that if the relief be caused by a ring of tinfoil attached to the tube, and connected by a wire to the inside of a rather large Leyden jar, it makes no difference whether the inside is connected to earth, or insulated and charged to any potential, positive or negative. And, further, the relief effect is equally well obtained when the tinfoil is connected to a large conductor of varying potential; as, for instance, the wire of an induction coil, as long as its period of variation is not the same as that producing the intermittence of the discharge.

The authors next show experimentally that

The relief effect (when the intermittence is effected near the positive terminal) assumes the form either of repulsion or of discharge from the interior surface of the glass. These two effects are identical in nature, and the form actually assumed depends in the same tube solely on the intensity of the action which calls it forth.

They also find that they can pass continuously from the repulsion to the discharge form of the relief effect in any one of three ways:—

(1) By keeping the relieving system fixed at the same spot on the tube, and varying the completeness of relief,* the discharge remaining the same.

(2) By keeping the relieving system constant, and varying its position on the tube, the discharge remaining the same.

(3) By keeping the relieving system constant and fixed in position, and varying the interruptedness of the discharge.

It is found, however, that only certain tubes give the discharge effect, but that they all give the repulsion effect.

On the Special or Non-relief Effects produced on the Sensitive Luminous Discharge by connecting it with the Air-spark Terminal.

Let us first suppose the intermittence to be caused by an interruption in the circuit between the source of electricity and the positive terminal of the tube. For convenience we shall express this fact by calling the positive terminal *the air-spark terminal.*

If we attach a wire to a piece of tinfol placed upon the

* As, for instance, by making the contact between the tinfoil and the earth wire an imperfect one.

tube, and connect the wire with any independent conducting system, we shall obtain, as we have seen, more or less complete forms of the relief effect. Both the wire and tinfoil will, in the majority of cases, repel the luminous column. But if the wire be connected with the *positive terminal*, a sudden change takes place in the phenomenon. Instead of the luminous column being repelled by the wire, the course of the latter along the tube (supposing it partly to rest upon the tube) will be marked by a bright line of luminosity on the inner surface of the glass as though it had attracted the luminous column instead of repelling it. And the effect of the tinfoil is changed in a no less remarkable manner. Instead of the former repulsion, a tongue of luminosity will be seen apparently starting from the actual inner surface of the glass under the tinfoil, and stretching toward the negative terminal of the tube, while the luminous column on the positive side of the tinfoil is usually depressed or repelled, and is often nearly severed in two. If the tinfoil be in the form of a ring round the tube, the appearance of the phenomena is very striking. In many cases the luminous column extending from the positive terminal is brought to an abrupt termination, and ends in a sharply-defined head, somewhat rounded at the extremity. Around this there is a well-marked hollow cone of luminosity, springing from the side of the tube immediately beneath the tinfoil, bright and sharply defined on the outside, but hazy and blue on the inside, which is turned to, and in fact surrounds, the termination of the positive column above described. This hollow cone does not come to an apex on its external surface, but passes into a luminous column which stretches away towards the negative terminal of the tube, and supplies the place of the former luminous column, which it resembles in all respects (fig. 183).

Fig. 183.

When the air-spark is considerably increased, the truncated luminous column is very much altered.

It will be observed that these effects are totally dissimilar to the relief effects.

Explanation of the Difference.

The difference is accounted for as follows:—

Each time that the discharge passes, there is a pulse of free positive electricity sent through the tube.

In the case of the relief effect, this is accompanied each time by a pulse of positive electricity driven *from* the tinfoil.

In the case of the non-relief effect, it is accompanied by a pulse of positive electricity driven *to* the tinfoil, and so the electric strain, instead of being relieved, is increased by the action of the tinfoil.

Examination of the Non-relief Effect.

The form of the non-relief effect obtained by making the positive the air-spark terminal may be taken as typical of all other forms of it.

If we place round the tube a narrow ring of tinfoil, and connect it with the positive terminal (where the air-spark is supposed to be) by a wire passing at a sufficient distance to prevent its directly affecting the luminous column, the following appearances will be noticed:—

(1) The column which starts from the positive terminal will be found suddenly to terminate in a bright column of small diameter occupying the centre of the tube. This column is usually striated, and ends in a stria with rounded head.

(2) On the side of the tinfoil towards the negative end a conical column of luminosity is seen to start from the inside of the tube immediately beneath the tinfoil, and to stretch towards the negative terminal. This cone in fact forms the base of the new positive column.

(3) On examination, this luminous cone is found to be hollow, the interior having an ill-defined and hazy surface in strong contrast with the somewhat sharp and regular outline of the exterior. (See fig. 183.)

The authors proceed to consider what is the explanation of these appearances. We know that strong pulsations of posi-

tive electricity pass to the positive terminal of the tube and the tinfoil, keeping time with the passage of the air-sparks. These pulsations, when they arrive at the terminal, are of sufficient intensity to cause discharges to pass through the tube, and the pulsations that reach the tinfoil must be of exactly the same strength as those that go to the terminal. Such pulsations must drive off positive electricity in corresponding pulsations from the interior parts of the tube contiguous to the tinfoil. These latter pulsations are similar to the discharges that take place from the positive terminal, and they seek relief in the same manner, viz., by rushing towards the negative terminal of the tube; in this process they form the hollow luminous cone mentioned above. These discharges of positive electricity from the inner surface of the tube leave behind them an excess of negative which would be held prisoned by the positive charge in the tinfoil if that were permanent; but just as the latter was generated by the momentary charging-up due to the passage of the air-spark, so it is released by the relief given to such charging-up by the discharge through the tube. On such discharge taking place, the negative on the interior of the tube is set free, and in its turn satisfies the positive that meets it from the positive terminal. Thus we naturally get the termination of one positive column on the side of the tinfoil nearest to the positive terminal, and a complete discontinuity between it and the second, which starts in a hollow cone from the edge of the tinfoil nearest to the negative terminal.

To show more clearly that this is the true interpretation of the phenomena, and that the effect of the arrangement is thus to substitute for the original discharge two independent discharges occupying different parts of the tube, take two or more such rings separated from each other by spaces somewhat less than the diameter of the tube, and connect them as before with the positive terminal (fig. 184). Each of these will be found to be the base of a hollow cone similar to that above described; and each such cone will form the base of a luminous column having all the features of a positive column, and terminating sharply behind the next tinfoil ring or at the borders of the usual negative dark place near to the negative terminal of the tube.

If we bring the finger or other conductor to the side of the tube, these columns will all display sensibility, but each will

move independently of the others and of the remainder of the positive column, and behave as if it started from the tinfoil ring at its base, still preserving, however, its position relative to the sectional columns on each side of it.

Fig. 184.

We now come to perhaps the most important portion of the paper, namely—that

On the Nature of Striæ, and the Artificial Production of Striation in the Luminous (Sensitive) Discharge.

We have seen that the positive discharge due to a ring of tinfoil forms a hollow cone with a sharply-defined luminous outer surface. This cone, if the nearest negative terminal is the negative terminal of the tube, passes into a column of diffused luminosity similar in all respects to the ordinary luminous column which starts from the positive terminal of a tube.

But if there is another similar ring of tinfoil connected with the positive terminal (we are assuming that the effect which is being examined is the special effect when the air-spark is in the positive circuit) between the former ring and the negative terminal, the luminous column that starts from ring No. 1 is stopped by ring No. 2, and from this latter ring there starts a second hollow luminous cone which stretches away in its turn towards the negative terminal in a different luminous column as before described.

If these rings be placed at the proper distance from one another, and the size and exhaustion of the tube be suitable, the short luminous column between the rings will dwindle down to a hollow cone with blunt rounded head, this head being greatly superior in brightness to any other part of the cone, and stretching to a point close up or to even a little within the next ring, so that it is in the middle of the space enclosed by the hazy blue inside surface of the hollow cone that starts from that ring.

And, by using additional rings, this can be made to repeat itself until the whole luminous column is segmented into these hollow luminous cones or shells with bright rounded heads.

The theory which the authors of the paper propose is that *each of these luminous cones or shells is a perfect stria both in function and structure.* The resemblance in appearance is most striking. There is the same convex bright outline pointing towards the negative terminal, the same hazy blue ill-defined hollow surface turned towards the shell immediately behind it, and there are the same dark intervals dividing consecutive shells as divide consecutive striæ. Flat and annular striæ can also be produced by proper adjustment of spark length, &c.

But it is not only in structure that these luminous shells resemble striæ. There is also an identity of function. We know that when the positive pulses arrive at the glass, they drive off similar positive pulses from the interior of the tube, and thus form the luminous shells. And knowing, therefore, that each luminous shell signifies a positive discharge, and also that no electricity passes through the glass, it is absolutely certain that a like amount of negative electricity must be collected at the surface of the glass within the tube, and must ultimately satisfy an equal amount of the original positive discharge—*i.e.*, of that which comes to it from the positive terminal, or from the shell immediately on the positive side of the one we are considering, as the case may be. We have then a negative discharge from the side of the tube, or from the gas immediately within it, satisfying a positive discharge advancing towards it along the tube; and we find that it causes the luminosity of this discharge to stop short and terminate in a bright, clearly-defined rounded head, which is separated by a dark space from the seat of the negative discharge. This, then, is the function of the shell: the bright part is to serve as the place of departure of the positive electricity that is about to pass across the dark space (or the place of arrival of the negative electricity after so doing), and the hazy interior of the cone is to form the place of its arrival (or the place of departure of the negative electricity); and, so far as we know, this is the sole function of these elements of the shell.

Now let us take the case of the striated discharge. Here, also, we know that the positive electricity in the current must

leave the bright head of the stria, and, after passing the dark space, arrive at the hazy inside of the next, and the negative electricity must take a reverse course. There is an absolute identity in the functions of the corresponding parts of the two structures, the only difference being that we know, from independent extrinsic evidence, that the electricity in the artificially segmented discharge does not flow continuously, but in intermittent discharges.*

Returning, then, to the case of the artificially produced conical shells, the *modus operandi* of the discharge is as follows:—When the pulse of positive electricity arrives at the terminal and causes the discharge into the tube, a positive discharge equal † to that which passes into the tube moves synchronously from the interior of the tube at each ring of tinfoil, forms the bright shell or stria, and passes on to the next shell or stria; thus supplying the place of the positive pulse that the ring of tinfoil there has just sent on. The last shell passes its discharge to the negative terminal, and the first shell receives a discharge from the positive terminal. In this way a discharge passes through the tube identical in quantity and character to that which passes into it from the positive terminal.

If, then, we are right in supposing that the series of artificially produced hollow shells are analogous in their structures and functions to striæ, it is not difficult to deduce, from the explanation above given, the *modus operandi* of an ordinary striated discharge. The passage of each of the intermittent pulses from the bright surface of a stria towards the hollow surface of the next may well be supposed by its inductive action to drive from the next stria a similar pulse, which in its turn drives one from the next stria, and so on. Thus the processes in the naturally and artificially striated columns are precisely similar, save that, in the case of the latter, the pulses from the several striæ are excited by

* At the present stage of the inquiry the authors assume that all vacuum discharges are in reality intermittent. Any who do not wish to admit this must take the reasonings of this section as applicable only to those striated discharges which are known to be intermittent.

† It may seem an unwarranted assumption to assume that each of these artificially produced discharges is equal to the whole original discharge, but the appearances (with suitable adjustments) seem to warrant it, and as the reasoning is simplified, and the validity of the theory is not affected by this assumption, it will, through the rest of this section, be supposed to be the case.

induction from without the tube, while, in the case of the former, the induction is that of the discharge itself in its passage from stria to stria. The passage of the discharge is due in both cases to an action consisting of an independent discharge from one stria to the next; and the idea of this action can perhaps be best illustrated by that of a line of boys crossing a brook on stepping-stones, each boy stepping on to the stone which the boy in front of him has left.

The unit of a striated vacuum discharge is therefore composed of the bright surface of a stria, the dark space in front of it, and the hazy interior surface of the stria on the further side of that dark space. In this unit we have a positive terminal, a space across which the discharge passes non-luminously, and a negative terminal. And, in the opinion of the authors of this paper, all striated vacuum discharges are composed of reduplications of this unit, and that any phenomena connected with the negative terminal which seem to contradict this view, and to point to a special structure of the discharge near the negative terminal, unlike anything that exists in other portions of the discharge, are merely modifications due to the local circumstances of the terminal.

The authors proceed to show that even the "negative glow" and "negative dark space" can be shown to be caused by modifications of a stria produced by the negative pole. The authors regard each segment as constituting a separate discharge. One phenomenon observed by them, of a different kind to those of which we have been chiefly speaking, appears strongly to confirm this. If a magnet be applied to a striated column, it will be found that the column is not simply thrown up or down as a whole, as would be the case if the discharge passed in direct lines from terminal to terminal, threading the striæ in its passage. On the contrary, each stria is subjected to a rotation or deformation of exactly the same character as would be caused if the stria marked the termination of flexible currents radiating from the bright head of the stria behind it, and terminating in the hazy inner surface of the stria in question. An examination of several cases has led the authors of this paper to conclude that the currents do thus radiate from the bright head of a stria to the inner surface of the next, and that there is no direct passage from one terminal of the tube to the other.

Physical Structure of Striæ.

It is natural to inquire what, in this theory, is the physical structure of striæ. Are they merely luminous appearances (i. e., loci of maximum luminosity), or are they aggregations of matter having a material structure?

The authors consider that this is a question which it is beyond the scope of this paper to discuss; but the most probable view, in their opinion, is that they should be regarded as *septa of complete electric porosity, having a material structure.* One of the most important facts favouring this conclusion is that when striæ are formed by a coil working with a high-speed break, the striæ produced by the two currents (the

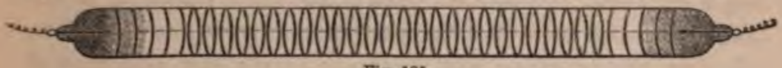


Fig. 185.

make and the break) adhere persistently together in pairs as though the alternate currents found ready to hand striæ that only needed a little deformation to make them available for their purposes. The authors add that there are other facts tending to support this conclusion, but that a complete examination of the question would carry them beyond the limits of the present paper.

Duration of the Discharge.

The passage of the discharge through the tube occupies a time which is sufficiently small in comparison with the interval between the discharges to prevent any interference between successive electrical pulses.

This was proved by an examination of the discharge by a revolving mirror.

In order further to test the possibility of single pulses giving rise to the effects of which we have been speaking, the following experiment was tried:—The terminals of a tube were connected with the outside and the inside of a small Leyden jar. The poles of the secondary circuit of a coil were placed so that the discharge from the coil charged the jar by leaping over intervals of considerable size (about a quarter of an inch for the negative pole, and three-quarters of an inch for the positive pole), so that the make-current was excluded. When the coil was worked, there appeared a brilliant discharge caused by the jar periodically

discharging itself through the column. A slit was placed on the tube, and the luminous column was examined by the revolving mirror, and it was found that the discharge was quite instantaneous, and that usually it was not followed by the next at any regular interval, but that occasionally it was multiple. The discharge was then tested for both relief and non-relief effects, and, notwithstanding the very large quantity that passed at each discharge, it gave them very markedly. The contact breaker was then worked by hand so as only to give single flashes. These were tested for sensitiveness and were found to be perfectly sensitive. *Thus it appears from experiment that the whole of the relief and non-relief effects are completed within each single pulsation, and that the effect of the rapid repetition of the discharges is merely to give the appearance of permanence to effects which in reality appear and disappear during each separate discharge.*

NATURE OF THE DISCHARGE.

The discharge is effected under ordinary circumstances by the passage through the tube from the air-spark terminal of free electricity of the same name as the electricity at that terminal.

The authors prove this proposition by numerous experiments, of which perhaps the two most important are the following:—

(1.) If a piece of tinfoil be placed at *any* part of the tube, even at the end farthest from the air-spark, the relief effect will be such as to show that the pulse of electricity is of the same kind at every portion of the inside of the tube.

(2.) In order to prove the proposition in another way, a vacuum-tube was enclosed in a metal canister (the wires passing to its terminals through tubes of insulating material inserted in small holes in the canister), and a telephone was placed in circuit between the canister and the earth. When a discharge with an air-spark in the external circuit was sent through the tube, a sound was heard in the telephone similar to that made by the air-spark. By a fundamental proposition in electricity* the free electricity on the surface of the canister (and which escaped through the telephone to the earth) was at any instant equal to the excess of one kind of electricity over the other in the space within the canister. Had the discharge been in the nature of conduction, as in a galvanic current, there would at no instant

* See vol. i. page 16.

have been an excess of either kind of electricity, and therefore there would not have been any sound in the telephone. The existence of a sound testified to variations in the algebraical sum of the free electricity in the tube. To show that this was not due to anything depending on the wires leading to the tube, the same experiment was repeated with a tube in which the middle portion was connected with the two end portions by very narrow passages. The middle portion was placed in the canister and the narrow parts passed through small holes made in its sides, so that only a portion of the complete tube was within the canister. The same results were obtained with this arrangement.

On Unipolar Discharges.

We have seen that, inasmuch as the discharge from the air-spark terminal produces its special effect without any indistinctness or confusion close up to the opposite terminal, it would appear that the discharges from the two terminals are so far independent that the discharge may take place from one, and the free electricity pass right through the tube to the immediate vicinity of the other, without evoking a specific response from the latter terminal. And if each such discharge does in any way call forth from the other terminal a specific response, it must be so slight that it does not affect materially the electrical condition of the interior of the tube, or the effect which that condition produces on conducting systems outside the tube. And we have also seen that this independence implies that the electricity leaves the terminal from which it starts in consequence of the electric tension within that terminal, and only in a very subordinate degree in consequence of the correlative action at the opposite terminal. Lest these should seem to be too hastily drawn conclusions, the authors proceed to describe a class of phenomena which furnish very important evidence of their truth.

If we take two exhausted tubes of the same general type, and connect one terminal of each with one terminal of a large Holtz machine, and connect their other terminals with the other terminal of the machine, interposing an air-spark (say in the positive circuit) so that the electricity has two alternative paths, the one through the one tube and the other through the other, the air-spark being common to both paths, a very remarkable phenomenon will be witnessed (fig. 186). If the air-spark be of a suitable

magnitude, it will be found that one of the tubes is wholly traversed by the discharge, but that the other is occupied only by a luminous column extending from the positive terminal into

Fig. 186.

the tube for a considerable portion of its length, and gradually tapering to a point. If the air-spark do not exceed a certain limit, depending upon the "resistance" of both tubes, there will be no luminosity at the other end of the tube, and no discharge through it. No effect will be produced upon the luminous column, nor on any portion of the discharge, by breaking the connection with the distant terminal, showing, what the appearance of the column itself sufficiently indicates, that the discharge is unipolar or incomplete. Slight indications of blue haze are sometimes seen at the tip of this tapering column, due probably to some negative electricity gathered from the neighbourhood, but not directly discharged from the opposite terminal. *The discharge is, in fact, one which passes into the tube, but not with sufficient force to pass through it, and which accordingly returns by the way by which it entered.* The cause of this recall will be examined later; for the present it suffices to point out the fact that here we have a discharge from one pole, which is unable to approach near enough to the other pole to get relief there, and actually prefers to return by the way it came rather than to pass through the tube to the other terminal. Such discharges the authors propose to call *unipolar discharges.*

This unipolar discharge is of course intermittent, and therefore sensitive. If we take a glass rod (fig. 187) with a piece of tinfoil at the extremity electrically connected by a wire with the positive terminal of the tube, and hold it near to but a little beyond the end of the luminous column, we shall find the luminous column driven back; and by carefully advancing it towards the positive terminal we can often succeed in driving the luminous column wholly

back and preventing any visible discharge taking place into the tube. The explanation of this is obvious. At the moment

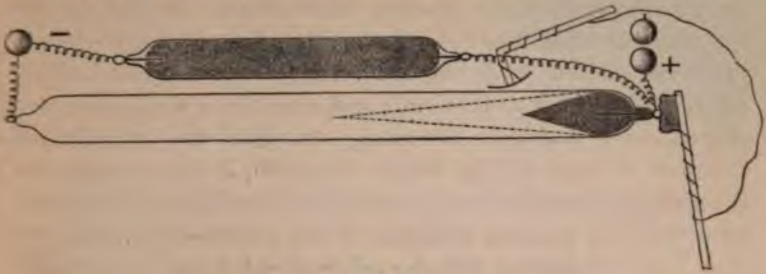


Fig. 187.

that the charging-up, which causes the discharge, takes place in the positive terminal, there is also a charging-up in the tinfoil, and this by its inductive effect tends to prevent the advance of any free positive electricity. Thus, however rapid the pulsation, the force tending to oppose the discharge keeps exact time with it, and causes the heading back of the luminous column. If the tinfoil and wire be connected with earth, or otherwise made a relieving system, we find the usual to-earth effects produced on this unipolar discharge.

A form of these experiments, which is in some respects even more striking, is obtained by taking a tube with an intermediate terminal (fig. 188), and connecting the inter-

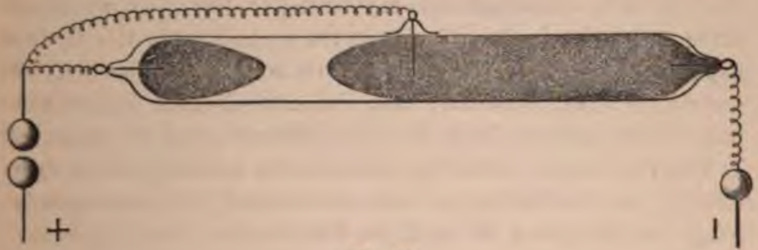


Fig. 188.

mediate and one of the end terminals with the positive terminal of the machine, and the other terminal of the tube with the negative terminal of the machine. Let us interpose an air-spark in the positive circuit so that it forms part of the path to both of the terminals which were connected with

the positive terminal of the machine. With an air-spark of proper dimensions it will be found that while the whole effective current passes from the positive intermediate terminal to the negative terminal, there is seen besides, first a tongue-shaped luminous column extending from the positive end terminal towards the intermediate terminal; and, secondly, a similar tongue-shaped luminous column stretching out from the intermediate terminal to meet it (fig. 188). Or again, if we arrange two tubes as first described, and connect both terminals of the second tube with the positive terminal of the machine (fig. 189), we shall have two positive unipolar columns as before. These two do not join; and it is clear that here we have naturally the same effect

Fig. 189.

as that obtained by the use of the tinfoil in the former case. Each of these discharges acts repulsively on the other, and they drive each other back. If we use the tinfoil, as in the former experiment (fig. 187), we can drive each in turn back towards, and sometimes into its terminal; and within considerable limits when one column is driven back, the other advances, and *vice versâ*.

This experiment with the intermediate terminal shows very forcibly how the discharge from an air-spark terminal depends solely on the forces at work at the terminal itself, and has but little reference to the condition of the other terminal of the tube. We see here that the positive electricity from the intermediate terminal actually issues copiously in the direction in which lies not only no negative terminal, but actually a positive terminal, which ultimately succeeds in repelling its advacen.

In corroboration of the statement that these tongue-shaped

luminous columns are parts of two distinct incomplete discharges, we may add that the magnet shows that they represent discharges going in opposite directions, the positive electricity in each proceeding from the base of each column towards the apex.

Similar phenomena, save in respect of the shape of the luminous columns, are seen when the two terminals are joined to the negative terminal of the machine.

In the course of their experiments the authors showed that, if we take a discharge of small quantity from a coil of symmetrical make, the electricity passes into the tube simultaneously at both terminals, and that the two discharges meet and form a neutral zone near the middle of the tube.

The result of connecting a small condenser with one of the terminals of the tube, when a coil discharge is used, is to depress the electrical tension produced at that terminal, and shift the position of the neutral zone. It is very instructive to compare these effects with the analogous effects in the case of unipolar discharges. If we join the effective terminal of the tube containing the unipolar discharge to a small condenser composed of, say, two pieces of tinfoil about three square inches in area, with a plate of mica between them, we shall see the luminous tongue slightly shorten. If, now, we connect the other side of this condenser to earth, we see a further shortening of the column, which will often almost disappear. If we connect the terminal with a larger condenser or a Leyden jar, the discharge wholly disappears. Thus we see that the condenser or Leyden jar has, just as in the case of the coil discharges, the effect of muffling or toning down the intensity of the impulsive changes of electrical tension at the terminals, and thereby lessening the violence of the discharges into the tube.

General Conclusion.

The authors conclude from these experiments that the independence of the discharge from each terminal is so complete that we can at will cause the discharges from the two terminals to be equal in intensity but opposite in sign (as in the case of the coil) or of any required degree of inequality (as in the case of the coil with a small condenser). Or we can cause the discharge to be from one terminal only, the other terminal acting merely recep-

tively (as in the case of the air-spark discharge); or we can cause the discharge to pass from one terminal only and return to it, the other terminal not taking any part in the discharge; or finally, we can make the two terminals pour forth independent discharges of the same sign, each of which passes back through the terminal from whence it came.

The paper concludes with an examination of

The State of the Tube during the Occurrence of the Discharge.

The authors find that the discharge does *not* take place simultaneously all along the tube, but that it is progressive, and proceeds from the air-spark terminal.

If two pieces of tinfoil, connected by a thin wire, be placed on the tube—a small one, A, near the air-spark terminal, and a large one, B, near the opposite terminal—it is found that a relief is obtained at A as complete as if B (still attached by a wire) were removed quite away from the tube.

This shows that, at the time when the demand for relief is being made on A, no such demand is being made on B—that is, that the discharge has not reached B at the time when it is passing A.

Concluding Remarks.

The authors proceed to inquire whether the results which they have established from discontinuous discharges are also applicable to continuous ones, and they conclude that the essentials of the discharge of electricity through rarefied gases are the same, whether the discharge be interrupted, uninterrupted, or wholly discontinuous, and perhaps alternate.

Now the simplest, and indeed the only obvious, explanation of this result is that the character which was found to be fundamental in sensitive discharges, viz., disruptiveness, is common to both kinds of discharge; and that the difference between the two kinds is to be sought in the scale on which that character is displayed.*

In both discharges, each terminal pours forth its electricity to satisfy its own needs, and only in a very secondary degree to satisfy the needs of the opposite terminal. The one terminal does

* It must be noted that in the ordinary discharge the discontinuous pulses in which the electricity leaves the terminals must be very minute.

not feel the electric state of the other directly, as would be the case were they metallically connected, but pours forth its electricity in the shape of free electricity, and leaves it to wander at its own will in that shape. If these two matters could be demonstrated conclusively, a great step would be gained in our knowledge of the nature of electric discharges; and, though the authors consider that this is not to be hoped for at present, they trust that the results recorded in this paper add considerably to the evidence in favour of them.

The authors conclude with a number of arguments in favour of the view that *all* discharges are discontinuous. In particular we may note that the probability that both kinds of discharge are really pulsatory is increased by the consideration that the striæ are *formed* by the discharge. This increases the difficulty of supposing that a strictly continuous current could imitate effects which we have seen to be caused by discharges known to be instantaneous and disconnected. If the evidence given in the paper of the form of the discharge from one stria to another (see vol. ii. page 101) be considered sufficient, these remarks have still greater weight, for it is scarcely conceivable that a strictly continuous current should take so strange a course. The passage from stria to stria must then be taken as disruptive and discontinuous; and, if this be granted, then, as striæ are only particular cases of terminals, it follows almost as a matter of course that all discharges in rarefied air are equally disruptive and discontinuous.

CHAPTER XXXVII.

PHENOMENA IN VERY HIGH VACUA—EXPERIMENTS OF CROOKES.*

Mr. Crookes states that he has discovered that when the exhaustion of a vacuum tube is carried considerably beyond that point which gives the best striæ and luminous effects, a new set of phenomena not hitherto observed are produced, and that the residual gas developes so many new properties that he considers himself justified in saying that gas, when at these low pressures, may be regarded as matter in a fourth or ultra-gaseous state. To this he has given the name of "Radiant Matter."

According to Mr. Crookes, the states of matter are four, as follow: —

1. Solid.
2. Liquid.
3. Gaseous.
4. Radiant.

Although this view has not met with universal acceptance, it still appears to me to be legitimate, for the differences between the 3rd and 4th state seem to me to be at least as great as those between the 2nd and 3rd, and certainly to be greater than those between the 1st and 2nd.

The pressure at which the new phenomena are best seen is about 1 **M** (one millionth of an atmosphere).

The difference between gas at 1 **M** and gas at say 3000 **M** appears chiefly to be caused by the fact that at the lower pressure the "Free Path" of each molecule—that is, the average distance which it moves without coming into collision with another molecule—is comparatively great, while at a higher pressure it is much smaller.

* "On Radiant Matter," a Lecture delivered to the British Association at Sheffield, August 22, 1879, by Wm. Crookes, F.R.S.

At the high pressure the molecules can hardly be said to move at all in straight lines, because their direction of motion is constantly being changed by collision. Speaking roughly, we may say that, at a pressure of 1 **M**, the "mean free path,"—that is, the average distance which each molecule will move in a straight line before being deflected by collision—is about 3000 times as long as its mean free path in gas at 3000 **M**, the pressure of an ordinary vacuum tube. In fact, as Mr. Crookes observes, "By great rarefaction the mean free path has become so long that the hits in a given time, in comparison to the misses, may be disregarded, and the average molecule is now allowed to obey its own motions or laws without interference. The mean free path, in fact, is comparable to the dimensions of the vessel, and we have no longer to deal with a *continuous* portion of matter, as would be the case were the tubes less highly exhausted, but we must here contemplate the molecules *individually*."

The Negative Dark Space.

In all well-exhausted vacuum tubes a small "dark space" surrounds the negative pole.

Mr. Crookes finds that, as the exhaustion improves, the dark space increases. He accounts for the increase as follows:—

Molecules of gas are driven off from the negative pole, and, as long as they do not come into collision with any other molecules, they do not produce any light. The space over which they travel without collision will be dark.

When, by diminishing the pressure, the mean free path is lengthened, the dark space increases.

The following experiment was devised for showing this "dark space" to an audience:—

The tube (fig. 190) has a pole at its centre in the form of a metal disk, and other poles at each end. The centre pole is made negative, and the two end poles connected together are made the positive terminal. The dark space will be in the centre. When the exhaustion is not very great, the dark space extends only a little on each side of the negative pole in the centre. When the exhaustion is good, as in the tube which was shown in the lecture, and the coil is turned on,

the dark space is seen to extend for about an inch * on each side of the pole.

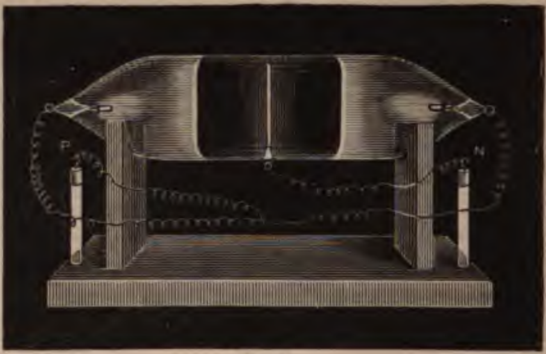


Fig. 190.

RADIANT MATTER EXERTS POWERFUL PHOSPHOROGENIC ACTION WHERE IT STRIKES.

We have mentioned that the radiant matter within the dark space excites luminosity where its velocity is arrested by residual gas outside the dark space. But if no residual gas is left, the molecules will have their velocity arrested by the sides of the glass; and here we come to the first and one of the most noteworthy properties of radiant matter discharged from the negative pole—its power of exciting phosphorescence when it strikes against solid matter. The number of bodies which respond luminously to this molecular bombardment is very great, and the resulting colours are of every variety. Glass, for instance, is highly phosphorescent when exposed to a stream of radiant matter. Fig. 191 represents three bulbs composed of

Fig. 191.

* Here the mean free path of the molecules would be about an inch.

different glass: one is uranium glass (*a*), which phosphoresces of a dark green colour; another is English glass (*b*), which phosphoresces of a blue colour; and the third (*c*) is soft German glass—of which most of the apparatus used in the lecture was made—and phosphoresces of a bright apple-green.

Many other substances are also phosphorescent under the influence of radiant matter.

When luminous sulphide of calcium, prepared according to Mr. Ed. Becquerel's description, is exposed even to candle-light, it phosphoresces for hours with a bluish white colour. It is, however, much more strongly phosphorescent under the influence of the luminous discharge in a good vacuum.

The rare mineral Phenakite (aluminate of glucinum) phosphoresces blue; the mineral Spodumene (a silicate of aluminium and lithium) phosphoresces a rich golden yellow; the emerald gives out a crimson light. But Mr. Crookes finds that, without exception, the diamond is the most sensitive substance he has yet met for ready and brilliant phosphorescence. A very curious fluorescent diamond was exhibited in the lecture, green by daylight, colourless by candle-light. It is mounted in the centre of an exhausted bulb (fig. 192), and the molecular discharge was

Fig 192.

directed on it from below upwards. On darkening the room, the

diamond was seen to shine with as much light as a candle, phosphorescing of a bright green.

Next to the diamond the ruby is one of the most remarkable stones for phosphorescing. A tube shown in fig. 193 was exhibited

Fig. 193.

containing a fine collection of ruby pebbles. As soon as the induction spark was turned on, the rubies were seen to shine with a brilliant rich red tone, as if they were glowing hot. It scarcely matters what colour the ruby is, to begin with. In the tube of natural rubies there were stones of all colours—the deep red and also the pale pink ruby. There were some so pale as to be almost colourless, and some of the highly-prized tint of pigeon's blood; but under the impact of radiant matter they all phosphoresced with about the same colour.

Now the ruby is nothing but crystallized alumina with a little colouring matter. In a paper by Ed. Becquerel,* published twenty years ago, he describes the appearance of alumina as glowing with a rich red colour in the phosphoroscope. In another tube was shown some precipitated alumina prepared in the most careful manner. It had been heated to whiteness, and under the molecular discharge it glowed with the same rich red colour.†

* *Annales de Chimie et de Physique*, 3rd series, vol. lvii., p. 50, 1859.

† The spectrum of the red light emitted by these varieties of alumina is the same as described by Becquerel twenty years ago. There is one intense red line, a little below the fixed line B in the spectrum, having a wave-length of about 6895. There is a continuous spectrum beginning at about B, and a few fainter lines beyond it, but they are so faint in comparison with this red line that they may be neglected. This line is easily seen by examining with a small pocket spectroscope the light reflected from a good ruby.

Fig. 194 represents a tube which was shown to illustrate the

Fig. 194.

dependence of the phosphorescence of the glass on the degree of exhaustion. The two poles are at *a* and *b*, and at the end (*c*) is a small supplementary tube connected with the other by a narrow aperture, and containing solid caustic potash. The tube had been exhausted to a very high point, and the potash heated so as to drive off moisture and injure the vacuum. Exhaustion had then been recommenced, and the alternate heating and exhaustion repeated until the tube had been brought to the state in which it was exhibited. When the induction spark was first turned on, nothing was visible—the vacuum was so high that the tube was non-conducting. The potash was then warmed slightly, so as to liberate a trace of aqueous vapour. Instantly conduction commenced, and the green phosphorescence flashed out along the length of the tube. The heat was continued so as to drive off more gas from the potash. The green got fainter, and then a wave of cloudy luminosity swept over the tube, and stratifications appeared, which rapidly got narrower, until the spark passed along the tube in the form of a narrow purple line. The lamp was taken away, and the potash allowed to cool; as it cooled, the aqueous vapour, which the heat had driven off, was reabsorbed. The purple line broadened out, and broke up into fine stratifications; these got wider, and travelled towards the potash tube. Then a wave of green light appeared on the glass at the other end, sweeping on and driving the last pale stratification into the potash; and, lastly, the tube glowed over its whole length with the green phosphorescence. If the tube is left to itself for some time, the green grows fainter and the vacuum becomes non-conducting.

Radiant Matter proceeds in Straight Lines.

The radiant matter, whose impact on the glass causes an evolution of light, absolutely refuses to turn a corner. Fig. 195

represents a V-shaped tube, a pole being at each extremity. The pole at the right side (a) being negative, the whole of the right

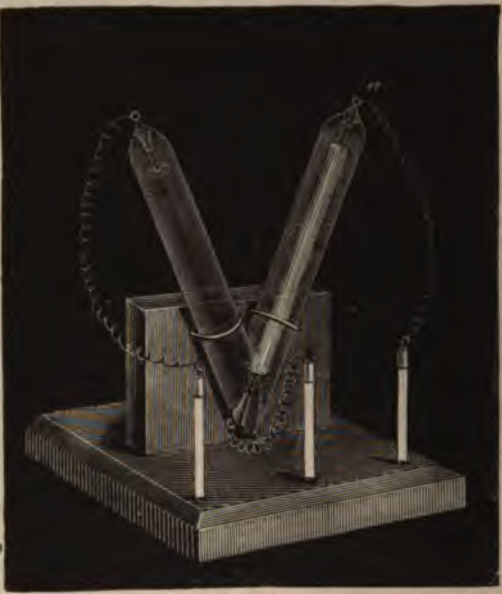


Fig. 196.

arm was flooded with green light, but at the bottom it stopped sharply and would not turn the corner to get into the left side. When the current was reversed, and the left pole made negative, the green changed to the left side, always following the negative pole, and leaving the positive side with scarcely any luminosity.

To produce the ordinary phenomena exhibited by vacuum tubes, it is customary, in order to bring out the striking contrasts of colour, to bend the tubes into very elaborate designs. The luminosity caused by the phosphorescence of the residual gas follows all the convolutions into which skilful glass-blowers can manage to twist the glass. The negative pole being at one end and the positive pole at the other, the luminous phenomena seem to depend more on the positive than on the negative at the ordinary exhaustion hitherto used to get the best phenomena of vacuum tubes. But at a very high exhaustion the phenomena noticed in ordinary vacuum tubes, when the induction spark passes through them—an appearance of cloudy luminosity and of stratifications—disappear

entirely. No cloud or fog whatever is seen in the body of the tube, and with such a vacuum as is used in these experiments, the only light observed is that from the phosphorescent surface of the glass. Fig. 196 represents two bulbs, alike in shape and

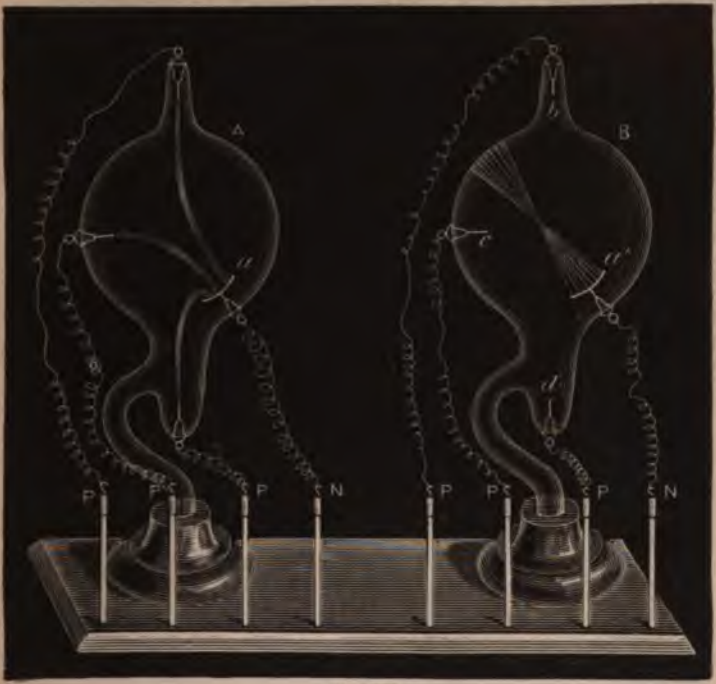


Fig. 196.

position of poles, the only difference being that one is at an exhaustion equal to a few millimetres of mercury—such a moderate exhaustion as will give the ordinary luminous phenomena—whilst the other is exhausted to about the millionth of an atmosphere. First the moderately exhausted bulb (A) was connected with the induction coil, and the pole at one side (*a*) being retained always negative, the positive wire was put successively to the other poles with which the bulb is furnished. It was seen that as the position of the positive pole was changed, the line of violet light joining the two poles changed, the electric current always choosing the shortest path between the two poles, and moving about the bulb as the position of the wires was altered.

This, then, is the kind of phenomenon we get in ordinary

exhaustions. The same experiment was then tried with a bulb (B) that was very highly exhausted, and, as before, the side pole (a') was made the negative, the top pole (b) being positive. The appearance seen was very widely different from that shown by the last bulb. The negative pole was in the form of a shallow cup. The molecular rays from the cup crossed in the centre of the bulb, and, thence diverging, fell on the opposite side and produced a circular patch of green phosphorescent light. The positive wire was removed from the top and connected first to the side pole (c), then to the bottom pole (d); but the green patch remained where it was at first, unchanged in position or intensity.

We have here another property of radiant matter. In the low vacuum, the position of the positive pole is of every importance, whilst in a high vacuum the position of the positive pole scarcely matters at all; the phenomena seem to depend entirely on the negative pole. If the negative pole points in the direction of the positive, all very well; but, if the negative pole is entirely in the opposite direction, it is of little consequence: the radiant matter darts all the same in a straight line from the negative.

Fig. 197.

If, instead of a flat disc, a hemi-cylinder is used for the negative pole, the matter still radiates normal to its surface. The tube represented in fig. 197 illustrates this property. It contains, as a negative pole, a hemi-cylinder (a) of polished aluminium. This is connected with a fine copper wire, b, ending at the platinum terminal, c. At the upper end of the tube is another terminal, d. The induction-coil is connected so that the hemi-cylinder is negative and the upper pole positive, and, when exhausted to a sufficient extent, the projection of the molecular rays to a focus is very beautifully shown. The rays of matter,

being driven from the hemi-cylinder in a direction normal to its surface, come to a focus and then diverge, tracing their path in brilliant green phosphorescence on the surface of the glass.

Another tube was shown, in which the focus of molecular rays was received on a phosphorescent screen instead of on the glass. The effect produced was most brilliant, and lighted up the whole table.

Radiant Matter, when intercepted by Solid Matter, casts a Shadow.

Radiant matter comes from the pole in straight lines, and does not merely permeate all parts of the tube and fill it with light, as would be the case were the exhaustion less good. Where there is nothing in the way, the rays strike the screen and produce phosphorescence; and where solid matter intervenes, they are obstructed by it, and a shadow is thrown on the screen. In the pear-shaped bulb (fig. 198) the negative pole (*a*) is at the

Fig. 198.

pointed end. In the middle is a cross (*b*) cut out of sheet aluminium, so that the rays from the negative pole projected along the tube will be partly intercepted by the aluminium cross, and will project an image of it on the hemispherical end of the tube which is phosphorescent. When the coil was turned on, the black shadow of the cross was clearly seen on the luminous end of the bulb (*c*, *d*). Now, the radiant matter from the negative pole has been passing by the side of the aluminium cross to

produce the shadow; the glass has been hammered and bombarded till it is appreciably warm, and at the same time another effect has been produced on the glass—its sensibility has been deadened. The glass has got tired, if the expression may be used, by the enforced phosphorescence. A change has been produced by this molecular bombardment which will prevent the glass from responding easily to additional excitement; but the part that the shadow has fallen on is not tired—it has not been phosphorescing at all, and is perfectly fresh; therefore, on the cross being thrown down * so as to allow the rays from the negative pole to fall uninterruptedly on to the end of the bulb, the black cross (*c*, *d*, fig. 199) was seen suddenly to change to a

Fig. 199.

luminous one (*e*, *f*), because the back-ground was now only capable of faintly phosphorescing, whilst the part which had the black shadow on it retained its full phosphorescent power. The stencilled image of the luminous cross soon dies out. After a period of rest the glass partly recovers its power of phosphorescing, but it is never so good as it was at first.

Here, therefore, is another important property of radiant matter. It is projected with great velocity from the negative pole, and not only strikes the glass in such a way as to cause it to vibrate and become temporarily luminous while the discharge is going on, but the molecules hammer away with sufficient energy to produce a permanent impression upon the glass.

Radiant Matter exerts Strong Mechanical Action where it Strikes.

We have seen, from the sharpness of the molecular shadows, that radiant matter is arrested by solid matter placed in its path.

* This could be done by giving the apparatus a slight jerk, the cross having been ingeniously constructed with a hinge by Mr. Gimingham.

If this solid body is easily moved, the impact of the molecules will reveal itself in strong mechanical action. Fig. 200 represents

Fig. 200.

an ingenious piece of apparatus, constructed by Mr. Gimingham, which, when placed in the electric lantern, rendered this mechanical action very plainly visible. It consists of a highly-exhausted glass tube, having a little glass railway running along it from one end to the other. The axle of a small wheel revolves on the rails, the spokes of the wheel carrying wide mica paddles. At each end of the tube, and rather above the centre, is an aluminium pole, so that, whichever pole is made negative, the stream of radiant matter darts from it along the tube, and, striking the upper vanes of the little paddle-wheel, causes it to turn round and travel along the railway. By reversing the poles the wheel can be arrested and sent the reverse way; and if the tube be gently inclined, the force of impact is observed to be sufficient even to drive the wheel up-hill.

This experiment therefore shows that the molecular stream from the negative pole is able to move any light object in front of it.

The molecules being driven violently from the pole, there should be a recoil of the pole from the molecules, and by arranging an apparatus so as to have the negative pole movable and the body receiving the impact of the radiant matter fixed, this recoil can be rendered sensible. Fig. 201 represents an apparatus whose appearance is not unlike an ordinary radiometer, with aluminium discs for vanes, each disc coated on one side with a film of mica. The fly is supported by a hard steel instead of glass cup, and the needle point on which it works is connected by means of a wire with a platinum terminal sealed into the glass. At the top of the radiometer bulb a second terminal is sealed in. The radio-

meter therefore can be connected with an induction-coil, the movable fly being made the negative pole.

For these mechanical effects the exhaustion need not be so high as when phosphorescence is produced. The best pressure for this electrical radiometer is a little beyond that at which the dark space round the negative pole extends to the sides of the glass bulb. When the pressure is only a few millims. of mercury, on passing the induction current a halo of velvety violet light forms on the metallic side of the vanes, the mica side remaining dark. As the pressure diminishes, a dark space is seen to separate the violet halo from the metal. At a pressure

Fig. 201.

Fig. 202.

of half a millim. this dark space extends to the glass, and rotation commences. On continuing the exhaustion the dark space further widens out and appears to flatten itself against the glass, when the rotation becomes very rapid.

Fig. 202 represents another piece of apparatus which illustrates the mechanical force of the radiant matter from the negative pole. A stem (*a*) carries a needle-point in which revolves a light mica fly (*b b*). The fly consists of four square vanes of thin clear mica, supported on light aluminium arms, and in the centre is a small glass cap which rests on the needle-point. The

vanes are inclined at an angle of 45° to the horizontal plane. Below the fly is a ring of fine platinum wire (*c c*), the ends of which pass through the glass at *d d*. An aluminium terminal (*e*) is sealed in at the top of the tube, and the whole is exhausted to a very high point.

By means of the electric lantern an image of the vanes was projected on the screen. Wires from the induction-coil were attached, so that the platinum ring was made the negative pole, the aluminium wire (*e*) being positive. Instantly, owing to the projection of radiant matter from the platinum ring, the vanes rotated with extreme velocity. Thus far the apparatus had shown nothing more than the previous experiments had prepared us to expect; but another phenomenon was then exhibited. The induction-coil was disconnected altogether, and the two ends of the platinum wire connected with a small galvanic battery; this made the ring *c c* red-hot, and under this influence it was seen that the vanes spun as fast as they did when the induction-coil was at work.

Here, then, is another most important fact. Radiant matter in these high vacua is not only excited by the negative pole of an induction-coil, but a hot wire will set it in motion with force sufficient to drive round the sloping vanes.

Radiant Matter is deflected by a Magnet.

We now pass to another property of radiant matter. The long glass tube, shown in fig. 203, is very highly exhausted; it

Fig. 203.

has a negative pole at one end (*a*) and a long phosphorescent screen (*b*, *c*) down the centre of the tube. In front of the negative pole is a plate of mica (*b*, *d*) with a hole (*e*) in it; and when the current was turned on, a line of phosphorescent light (*e*, *f*) was projected along the whole length of the tube. A powerful horse-shoe magnet was now placed beneath the tube, and

the line of light (e, g) became curved under the magnetic influence, waving about like a flexible wand as the magnet was moved to and fro.

This action of the magnet is very curious, and, if carefully followed up, will elucidate other properties of radiant matter. Fig. 204 represents a tube exactly similar, but having at one

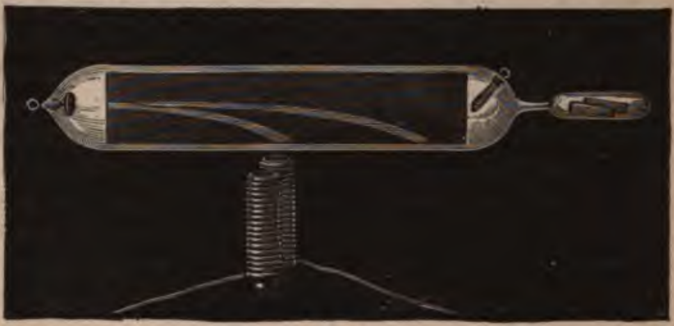


Fig. 204.

end a small potash tube, which, if heated, will slightly injure the vacuum. When the induction current is turned on, the ray of radiant matter is seen tracing its trajectory in a curved line along the screen, under the influence of the horse-shoe magnet beneath. Let us observe the shape of the curve. The molecules shot from the negative pole may be likened to a discharge of iron bullets from a mitrailleuse, and the magnet beneath will represent the earth curving the trajectory of the shot by gravitation. The curved trajectory of the shot is accurately traced on the luminous screen. Now suppose the deflecting force to remain constant, the curve traced by the projectile varies with the velocity. If more powder be put in the gun, the velocity will be greater and the trajectory flatter; and if a denser resisting medium be interposed between the gun and the target, the velocity of the shot will be diminished, and it will move in a greater curve and come to the ground sooner. The velocity of this stream of radiant molecules cannot well be increased by strengthening the battery, but they can be made to suffer greater resistance in their flight from one end of the tube to the other. In the experiment shown, the caustic potash was heated with a spirit-lamp, and so a trace more gas was thrown in. Instantly the stream of radiant matter responded. Its velocity was impeded, the magnetism,

had longer time on which to act on the individual molecules, the trajectory became more and more curved until, instead of shooting nearly to the end of the tube, the "molecular bullets" fell to the bottom before they had got more than half-way.

It is of great interest to ascertain whether the law governing the magnetic deflection of the trajectory of radiant matter is the same as has been found to hold good at a lower vacuum. The experiments just described were made with a very high vacuum. Fig. 205 represents a tube with a low vacuum. When

Fig. 205.

the induction spark is turned on, it passes as a narrow line of violet light joining the two poles. Underneath is a powerful electro-magnet. On making contact with the magnet, the line of light dips in the centre towards the magnet. On reversing the poles, the line is driven up to the top of the tube. We notice the difference between the two phenomena. Here the action is temporary. The dip takes place under the magnetic influence; the line of discharge then rises and pursues its path to the positive pole. In the high exhaustion, however, after the stream of radiant matter had dipped to the magnet, it did not recover itself, but continued its path in the altered direction.

By means of the little wheel (fig. 206) skilfully constructed by Mr. Gimingham, Mr. Crookes was able to show the magnetic deflection in the electric lantern. The negative pole (*a*, *b*) is in the form of a very shallow cup. In front of the cup is a mica screen (*c*, *d*), wide enough to intercept the radiant matter coming from the negative pole. Behind this screen is a mica wheel (*e*, *f*) with a series of vanes, making a sort of paddle-wheel. So arranged, the molecular rays from the pole *a b* will be cut off from the wheel, and will not produce any movement. A magnet *g* was now put over the tube, so as to deflect the stream over or under the obstacle *c d*, and the result was rapid motion in one or

the other direction, according to the way the magnet was turned. The image of the apparatus was thrown on the screen. The

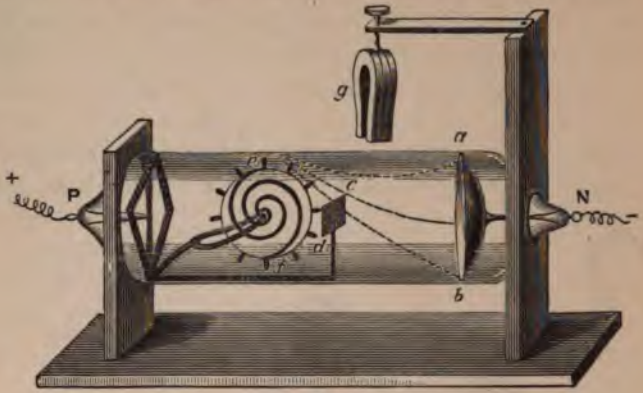


Fig. 206.

spiral lines painted on the wheel showed which way it turned. The magnet was arranged to draw the molecular stream so as to beat against the upper vanes, and the wheel revolved rapidly as if it were an over-shot water-wheel. On turning the magnet so as to drive the radiant matter underneath, the wheel slackened speed, stopped, and then began to rotate the other way, like an under-shot water-wheel. This reversal can be repeated as often as the position of the magnet is reversed.

We have mentioned that the molecules of the radiant matter discharged from the negative pole are negatively electrified. It is probable that their velocity is owing to the mutual repulsion between the similarly electrified pole and the molecules. In less high vacua, such as that shown in fig. 205, the

Fig. 207.

discharge passes from one pole to another, carrying an electric current as if it were a flexible wire. Now it is of great interest

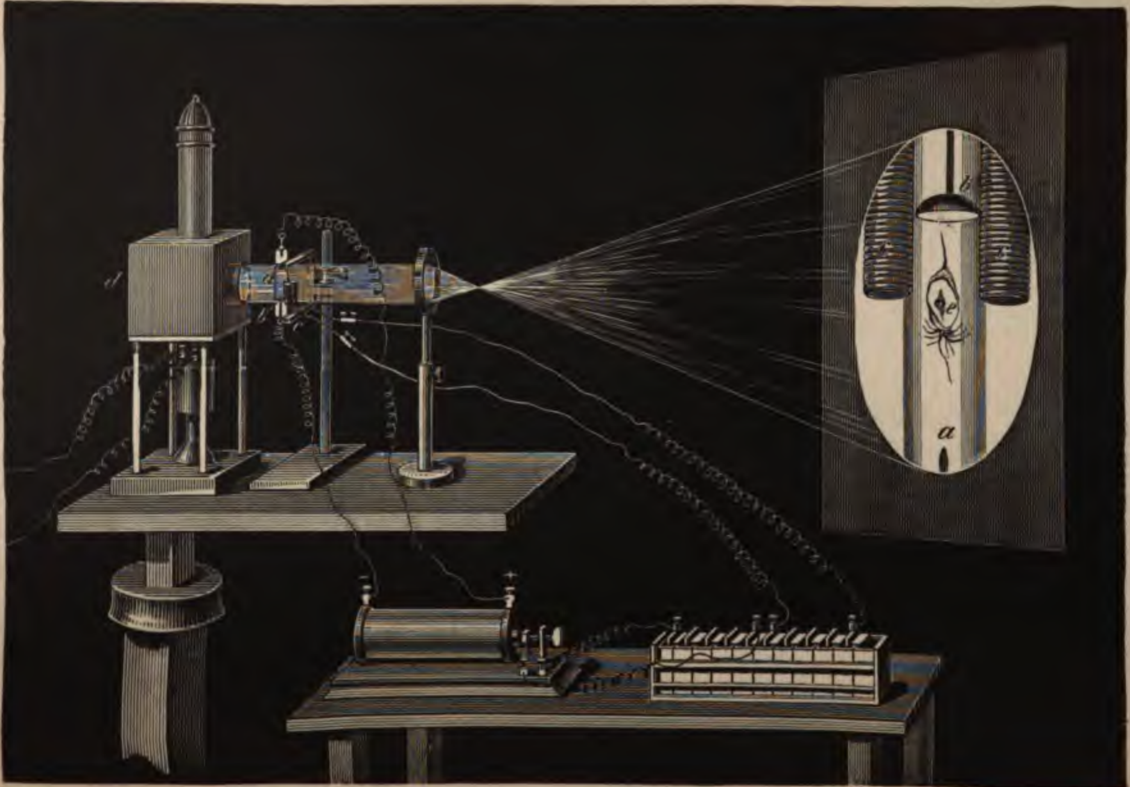


Plate XLVI.—Crookes' Radiant Matter.

to ascertain if the stream of radiant matter from the negative pole also carries a current. Fig. 207 is an apparatus which decides the question at once. The tube contains two negative terminals (*a*, *b*) close together at one end, and one positive terminal (*c*) at the other. This enables two streams of radiant matter to be sent side by side along the phosphorescent screen; or, by disconnecting one negative pole, only one stream.

If the streams of radiant matter carry an electric current, they will act like two parallel conducting wires and attract one another; but if they are simply built up of negatively electrified molecules, they will repel each other.

The upper negative pole (*a*) was first connected with the coil, and the ray was seen shooting along the line *d*, *f*. The lower negative pole (*b*) was then brought into play, and another line (*e h*) darted along the screen. Instantly the first line sprung up from its first position, *d f*, to *d g*, showing that it was repelled, and the lower ray was also deflected downwards: *therefore the two parallel streams of radiant matter exerted mutual repulsion, acting not like current carriers, but merely as similarly electrified bodies.*

Radiant Matter produces Heat when its Motion is arrested.

Another property of radiant matter is that the glass gets very warm where the green phosphorescence is strongest. The molecular focus on the tube (fig. 197) is intensely hot.

An apparatus was exhibited by which this heat at the focus was made visible to the audience.

A small tube (fig. 208) was prepared with a cup-shaped negative pole. This cup projects the rays to a focus in the middle of the tube. At the side of the tube is a small electro-magnet, which can be set in action by touching a key, and the focus is then drawn to the side of the glass tube (fig. 209). To show the first action of the heat the tube was coated with wax. The apparatus was put in front of the electric lantern, and a magnified image of the tube was thrown on the screen. (Plate XLVI.) The coil was set to work, and the focus of molecular rays was projected along the tube. The magnetism was turned on, and the focus drawn to the side of the glass. The first thing seen was a small circular patch melted in the coating of wax. The glass soon began to disintegrate, cracks shooting starwise from the centre of heat. The glass softened, next the atmospheric pressure

forced it in, and then it melted. A hole (*e*) was perforated in the middle, the air rushed in, and the experiment was at an end.

We can render this focal heat more evident if we allow it to play on a piece of metal. The bulb (fig. 210) is furnished with a negative pole in the form of a cup (*a*). The rays will therefore be projected to a focus on a piece of iridio-platinum (*b*) supported in the centre of the bulb.

Fig. 208.

Fig. 209.

Fig. 210.

The induction-coil was first slightly turned on so as not to bring out its full power. The focus played on the metal, raising it to a white heat. By bringing a small magnet near, the focus of heat was deflected just as was the luminous focus in the other tube. By shifting the magnet the focus can be driven up and down, or drawn completely away from the metal, so as to leave it non-luminous. On withdrawing the magnet so as to let the molecules have full play again, the metal became white-hot. On increasing the intensity of the spark, the iridio-platinum glowed with almost insupportable brilliancy, and at last melted.*

* The highest vacuum Mr. Crookes has yet succeeded in obtaining has been the 1-20,000,000th of an atmosphere, a degree which may be better understood if we say that it corresponds to about the hundredth of an inch in a barometric column three miles high.

CHAPTER XXXVIII.

ELECTROLYSIS.

Description of the Phenomenon.

If a binary compound body in a liquid state has a current of electricity passed through it, it is in general decomposed into its constituent elements, one of which appears at each of the points where the current enters and leaves the liquid.

If two platinum wires be immersed in acidulated water, and connected to a battery, the water will be decomposed; and hydrogen will appear at the negative pole, oxygen at the positive, and the volume of the hydrogen produced will always be double that of the oxygen.

If a solution, say of sulphate of copper, is substituted for the acidulated water, copper is deposited on the negative pole, while sulphuric acid is liberated at the positive.

Faraday's Nomenclature.*

The process of resolving compound bodies into their constituents is called *Electrolysis*. The bodies acted on are called *Electrolytes*. The poles at which the decomposition takes place are called *Electrodes*.

The electrode attached to the zinc of the battery is called the *cathode;* and the other, the *anode*.

The products of decomposition are called *ions;* those which go to the anode are called *anions* and those which go to the cathode *cations*.

Thus chloride of lead is an *electrolyte*, and when *electrolysed*, by having the *electrodes* of a battery immersed in it, evolves the two *ions*, chlorine and lead, the former being an *anion*, the latter a *cation*.

* "Exp. Res.," 665, vol. i. p. 197.

Laws of Electrolysis.*

No elementary substance can be an electrolyte.

For by definition, an elementary substance is that which cannot be separated into two constituents.

Electrolysis only occurs while the body is in the liquid state.

The free mobility of the particles is a necessary condition of electrolysis, for the process can only take place in one of two ways.

The molecule next one of the electrodes is decomposed. One constituent of it goes to the near electrode, and the other *either* travels to the other electrode *or* combines with a constituent of the molecule next to it, setting free a portion similar and equal to itself; which in its turn combines with the corresponding portion of the molecule next to it, and so on. In either case the free mobility of the particles is an essential condition.

Nevertheless, electrolysis sometimes occurs in viscous solids; but only in proportion to their fluidity.

Fused nitre is an excellent conductor in the liquid state. If, however, a cold platinum wire connected to a battery be dipped into it, electrolysis does not commence till the crust of solid nitre, which is formed round the cold wire, has had time to re-melt.

On this point Professor Maxwell† says,—

"Clausius,‡ who has bestowed much study on the theory of the molecular agitation of bodies, supposes that the molecules of all bodies are in a state of constant agitation, but that in solid bodies each molecule never passes beyond a certain distance from its original position, whereas, in fluids, a molecule, after moving a certain distance from its original position, is just as likely to move still farther from it as to move back again. Hence the molecules of a fluid apparently at rest are continually changing their positions, and passing irregularly from one part of the fluid to another. In a compound fluid he supposes that not only the compound molecules travel about in this way, but that, in the collisions which occur between the compound molecules, the molecules of which they are composed are often separated and change partners, so that the same individual atom is at one time

* See Miller's "Chemistry," 4th ed. vol. i. p. 516.

† Maxwell's "Electricity," 256, vol. i. p. 309.

‡ Pogg. Ann. Bd. ci. S. 338 (1857).

associated with one atom of the opposite kind, and at another time with another.

"This process Clausius supposes to go on in the liquid at all times; but when an electro-motive force acts on the liquid, the motions of the molecules, which before were indifferently in all directions, are now influenced by the electro-motive force, so that the positively charged molecules have a greater tendency towards the cathode than towards the anode, and the negatively charged molecules have a greater tendency to move in the opposite direction. Hence the molecules of the cation will, during their intervals of freedom, struggle towards the cathode; but will continually be checked in their course by pairing for a time with molecules of the anion, which are also struggling through the crowd, but in the opposite direction."

The direction of the molecules is always the same with regard to the direction of the battery current.

The following very instructive experiment for showing the definite direction of electrolytic force is due to the late Dr. W. A. Miller. He says,—

"Let* four glasses be placed side by side as represented in fig. 211, each divided into two compartments by a partition of card

Fig. 211

or three or four folds of blotting paper, and let the glasses be in electrical communication with each other by means of platinum wires which terminate in strips of platinum foil. Place in the glass No. 1 a solution of potassic iodide mixed with starch; in No. 2, a strong solution of common salt, coloured blue with sulphate of indigo; in 3, a solution of ammonium sulphate, coloured blue with a neutral infusion of the red cabbage; and in 4, a solution of cupric sulphate. Let the plate H be connected with

* Miller's "Elem. Chem.," vol. i. p. 517.

the positive wire, and let A complete the circuit through the negative wire. Under these circumstances iodine will speedily be set free in B, and will form the blue iodide of starch; chlorine will show itself in D, and will bleach the blue liquid; sulphuric acid will be seen in F, and will redden the infusion of cabbage; sulphuric acid will also be liberated in H, as may be seen by introducing a piece of blue litmus paper, which will immediately be reddened; whilst a piece of turmeric paper will be turned brown in A, from liberated potash; in C, it will also be turned brown by the soda set free; in E, the blue infusion of cabbage will become green from the ammonia which is disengaged; and in G, metallic copper will be deposited on the platinum foil."

For a constant quantity of electricity, whatever the decomposing conductor may be, whether water, saline solutions, acids, fused bodies, &c., the amount of electro-chemical action is a constant quantity. That is, the same quantity of electricity will always produce the same amount of chemical effect.*

The same current electrolyses different quantities of different substances, but the proportion of one to the other depends *only* on their chemical equivalents.

Thus, if a current from a battery be sent through a series o troughs containing respectively,—

Water	(H_2O),
Fused plumbic iodide	(PbI_2),
Fused stannous chloride . . .	($SnCl_2$)

then for each 65 milligrammes of zinc dissolved in any one cell of the battery, there will be produced,—

$(2 \times 1) = 2$	milligrammes	of hydrogen,
16	"	of oxygen,
207	"	of lead,
$(2 \times 127) = 254$	"	of iodine,
118	"	of tin, and
$(2 \times 35{\cdot}5) = 71$	"	of chlorine;

and these numbers,—

65, 1, 16, 207, 127, 118, 35.5

correspond to the chemical equivalents of the elements respectively.

If three similar vessels A, B, C, with platinum plates, and con-

* Faraday's "Exp. Res.," 505, vol. i. p. 145.

taining acidulated water, be arranged as in fig. 212, and a battery

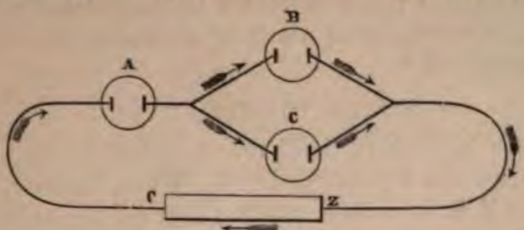


Fig. 212.

current passed through them, the sum of the quantities of gas produced in B and C will be exactly equal to that produced in A.

THE VOLTAMETER.

This fact enabled Faraday to invent the *Voltameter*, which consists of a trough containing acidulated water, and having electrodes inserted in it. Receivers over the electrodes collect the gas produced. *The quantity of gas produced per minute is an absolute measure of the mean strength of the current* during that time; and the total quantity of gas is a measure of the total strength of the current.*

It is necessary to collect the gases separately, as chemically clean platinum has the power of inducing their recombination.†

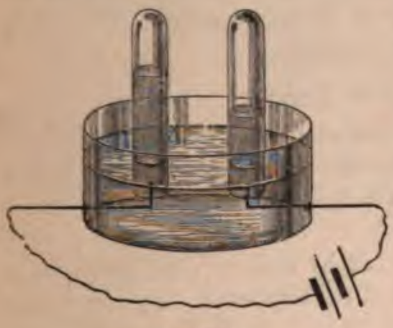


Fig. 213.

Fig. 213 shows a common form of the instrument.

The tubes are previously filled with water and inverted over the electrodes. As the gas rises it displaces the water. The amount of gas formed is known by graduations on the tubes.

Electrolysis is of great practical importance, for nearly all the

* For instance, if C were the strength of the current, measured by a tangent galvanometer, and A, the quantity of gas produced between the times t_1 and t_2, we may write $A = k\int_{t_1}^{t_2} C\,dt$, where k is a constant.

† Faraday, "Exp. Res.," Series vi. vol. i. pp. 165—194.

operations of plating, whether with copper, silver, or gold, are performed by making the substance to be plated, the negative electrode in a solution of a salt of the metal with which it is desired to plate it.*

Electrolytic Polarization.

We have hitherto supposed the currents to be strong enough to decompose the liquids employed. When, however, only one Daniell's cell is used, decomposition does not take place; but a state of "polarization" or strain is set up which very closely resembles that set up in a charged Leyden jar.

In fact, electrolytic polarization may be compared to the ordinary charging of a Leyden jar, and decomposition to the case where the charge of the jar is strong enough to perforate the glass.

Messrs. Ayrton and Perry † have measured the rate of charging of a voltameter, and the rate of the return of the charge, and they have found a very close resemblance between the electrolytic curves and those obtained for the charging and discharging of a Leyden jar.

They have also found‡ that both the electrolysis and the Leyden jar curves are precisely similar to those expressing the deflection of a beam by weights, and its return when the weights are removed, and that the same form of mathematical (differential) equation will express all three phenomena.

Measurement of Deflections.

The rapidly changing currents and potentials were measured by means of a reflecting galvanometer and electrometer whose light-spots were thrown on to a large rapidly revolving barrel covered with white paper.

The limits of swing were noted by making rapid dots with a pencil at the extreme positions of the light-spot. By this means two curves were obtained (fig. 214, 1, 3, 5, 7, and 2, 4, 6.) It is clear that the curve A, B, . . . E, expressing the mean value of the current or potential, must lie somewhere between these curves.

The authors show mathematically that each point on the

* Miller's "Chemistry," vol. i. pp. 541—548.

† Journal of Soc. of Telegraph Engineers, 1877, vol. v., Nos. xv., xvi. p. 391.

‡ See vol. i. p. 66.

mean curve may be obtained by bisecting that portion of the ordinate which lies between the extreme curves.

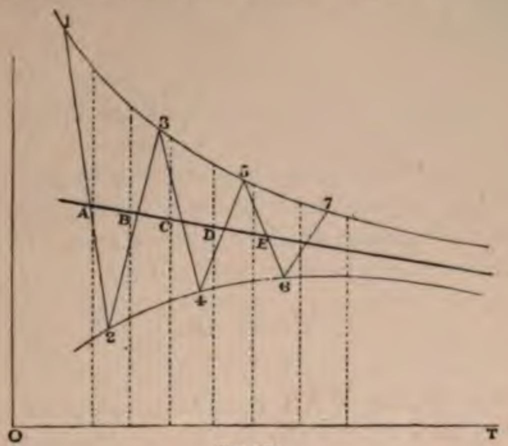


Fig. 214.

We see that the zigzag line 1, 2, 3, 4, 5, 6, 7, is the path of the spot of light.

Method of Experimenting.

Two platinum plates, each ten by eight centims., were placed 21·3 centims. apart in a mixture of pure water and sulphuric acid (sp. gr. of mixture 1·016 at 50° Fahr.).

These plates could be connected by means of a key to one Daniell's cell, the current flowing in at any time being measured by a galvanometer.

The plates were kept permanently connected to a quadrant electrometer by which their potentials could be measured.

When the circuit was broken, the plates were left insulated, and subsequently connected by resistance coils, and a very delicate reflecting galvanometer, by means of which the "return current" or "residual charge" was measured.

The time of any observation was noted by means of a "break-circuit chronograph." This consists of a rapidly-running "Morse Ink-writer," in which a pen is held down by an electro-magnet upon a rapidly-moving ribbon of paper and produces a continuous line as long as the current flows in the electro-magnet. At the commencement of each second, a clock breaks the circuit for a moment, producing a gap in the line.

At the instant of any event, which it is desired to record, the circuit is broken by hand or otherwise, and a gap made in the line whose position between the two nearest time-gaps gives the time of the event.

Results.

The first result obtained was that, at the instant of making contact, there is an enormously large current into the voltameter, far greater than the experimenters were able to measure.

In fig. 215, time is measured along OX, starting from O, which represents the moment of closing the circuit. Galvanometer and electrometer deflections are measured along OY.

Curve AB.

The curve expressing the fall of battery current is something of the shape of that of AB (fig. 215), only that during the first quarter of a minute the ordinate of the curve would be much greater than OA.

This is analogous to the fact that a rapid stream of sparks can be sent into a Leyden jar for a few seconds until it is charged, after which it will not receive any more.

Curve A′B′CC′.

The ordinates of this curve represent electrometer deflections.

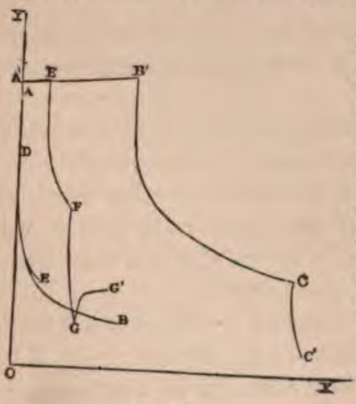


Fig. 215.

The line A′B′ represents the rise of potential during forty-six minutes, during which the battery was kept connected to the electrometer. At the end of that time the battery was disconnected, and the plates left insulated, except that they were connected through the acidulated water.

The fall of the potential is represented by the curve B′C.

After sixty-six minutes more, they were connected through 12,000 Ohms resistance, and the curve CC′ shows the fall of potential to the end of the experiment.

Curves DE, A EFGG′.

When the voltameter was connected to the battery, the current diminished rapidly. The fall during eleven minutes is represented by the curve DE.

During the same time the potential increased from A′ to E. At E the plates were insulated, and EF shows the fall of potential. At F, twenty-two minutes from the commencement of the experiment, the plates were connected through 12,594 Ohms, and in $3\frac{3}{4}$ minutes the potential fell to G.

The plates were than again insulated, and the potential rose to G′.

The shape of the curve GG′ is exactly similar to a curve obtained by the "soaking out" of the residual charge in a Leyden jar which has been discharged for a short time, and then insulated.

CHAPTER XXXIX.

SECONDARY BATTERIES—RHEOSTATIC MACHINES.

WHEN a current is sent through a voltameter for a considerable time, the plates acquire some sort of electrical polarization, such that, if the battery be removed and the plates connected by a wire, a current will be observed in the wire in the reverse direction to that of the battery current.

When the plates of the voltameter are made very large, it takes a longer time to polarize the plates, but the reversal or "secondary" current is extremely powerful. The secondary current only lasts a short time, but its total energy is equal to the total energy which it has received from the battery in a long time, and, therefore, during the time which it lasts, the secondary current will be much stronger than the "primary" or battery current.

Advantage has been taken of this fact in the construction of "secondary batteries," which enable us with two or three cells of Grove or Bunsen to obtain, for a short time, effects equal to those which could only be obtained directly by the use of many hundred cells.

PLANTÉ'S RESEARCHES.

The most important researches which have been made on secondary batteries are those of M. Gaston Planté,* now (Feb. 1880) in course of publication.

The form of "Secondary Element" which he uses is shown in

* "Recherches sur l'Électricité," par Gaston Planté. (Paris: A. Fourneau.)
Tom. I., 14 Fev., 1879.
Tom. II., fasc. i., 30 Sept., 1879.
Tom. II., fasc ii., 16 Oct., 1879.

fig. 216. It consists of two large sheets of lead, of rather more than one square metre area, kept apart by narrow bands of gutta-percha, and immersed in diluted sulphuric acid of the strength 10 to 1.*


Fig. 216.

Any number of these secondary elements can be connected so as to form a secondary battery.

M. Planté has also constructed batteries consisting of a series of flat lead plates, immersed in acid, arranged alternately like the plates of a condenser.†

When a secondary battery, consisting of six plates, each 0·20 metre by 0·22, and having an available surface of about $\frac{1}{2}$ a square metre, was excited by two Bunsen cells, the secondary current produced was found to be strong enough to heat to redness wires of iron, steel, and platinum one millim. in diameter.

"Formation" of the Plates.

It was found that, when the plates had been in use some time, they gave better effects than when they were new. An investigation of the conditions under which their action improved led M. Planté ‡ to the discovery of a method of "forming" the plates—that is, of causing them to assume the best condition for the production of the desired effects.

It is found that two or three Bunsen or Grove cells will produce a better "formation" than any number of Daniell's.

The process is as follows :—

On the first day the secondary element is charged alternately in the two directions some five or six times, and discharged between each reversal of the primary.

It will be found that the secondary current gets stronger after each reversal.

* Planté, Tom. I., p. 35.
† See vol. i. p. 67.
‡ Planté, Tom. I., pp. 49—55.

The six chargings are as follows, where "positive" means one direction of the current, "negative" the other direction.

1	Current	+	for	¼	hour.
2	"	—	"	¼	"
3	"	+	"	½	"
4	"	—	"	½	"
5	"	+	"	1	"
6	"	—	"	1	"

After the last charging, the secondary element is not discharged, but is left charged (—) until the next day.

The next day it is charged alternately + and — several times, each charging lasting 2 hours, after which it is found that the secondary current does not increase any more.

The element is then left at rest, charged (—) for 8 days, when it is again charged + but not reversed again that day. Then it is allowed to rest for 15 days, then for one month, two months, &c., and it is found that its power still goes on increasing, the increase being only limited by the thickness of the lead plates.

The improvement appears to be caused by the penetration of the electrolytic action into the interior of the plates, and the intervals of rest are necessary in order that the crystalline layers which are found to be formed in the metal may have time to harden before the reversal of the current.

Connection in Series or Side by Side.

A number of secondary elements can be connected either in "series" or "side by side" in precisely the same way as a number of ordinary battery cells (Vol. I., page 267), and with exactly similar results.

Heating Effects of the Secondary Currents.

If four or five elements be connected "side by side," and then discharged through a short thick iron wire, it will be fused into a ball as in fig. 217.

Fig. 217.

The surface of the incandescent ball will appear to "boil," and will be covered with spots, as bubbles of gas burst through from the interior.

The bulbs develope themselves very rapidly, and generally end

by bursting the envelope of liquid iron which surrounds them, and flying to pieces. Sometimes, however, the wire fuses first, and the ball cools and is preserved.

Magnetic Effects.

The secondary currents are able to magnetize electro-magnets much more powerfully than the primary currents from which they are derived.

Duration of the Secondary Currents.*

The secondary currents last longer when the plates have been well "formed" than when they are new.

Their duration also depends on the resistance through which they are being discharged, being of course longer when the resistance is high.

The discharge of one element will keep a platinum wire of one millim. diameter red hot for from one to ten minutes according to the degree of its "formation."

An element which will only keep a thick wire red hot for a few minutes will keep a platinum wire $\frac{1}{5}$ millim. in diameter in a state of incandescence for a full hour.

Constancy of the Current.

It is found, when the resistance is considerable, that the current remains sensibly constant during the time which it lasts.

Preservation of the Charge.

It is found that a well-"formed" element will give a good current two or three weeks after it has been charged.

Electro-motive Force.

It is found that the electro-motive force given by one element is about 1·45 to 1·50 times that of a Bunsen cell, i.e. about 2·5 volts.

Transformation of the Current of a Voltaic Battery by means of a Secondary Battery.†

In order to obtain currents of high potential, a number of secondary elements are arranged "side by side" and charged, and

* Planté, Tom. I., p. 65.
† Ibid., p. 93.

then are connected in series. While the elements are being charged, they are arranged as in fig. 218.

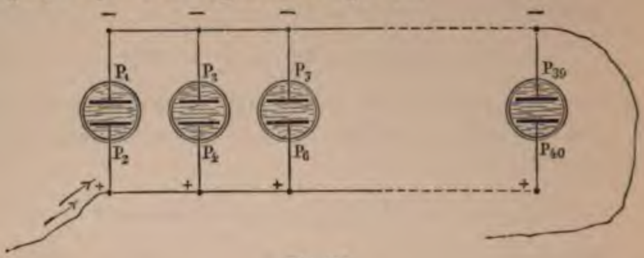


Fig. 218.

The connections are then altered to the arrangement of fig. 219, when the differences of potential given to each element separately

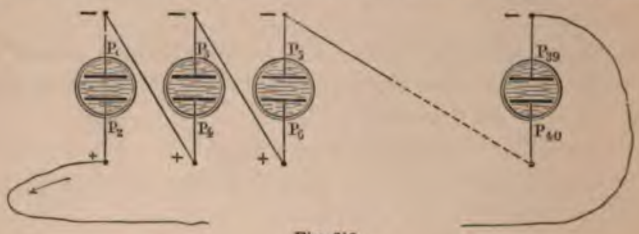


Fig. 219.

are all added together and produce a great difference of potential at the ends of the battery.

Fig. 220 represents an ingenious mechanical contrivance for

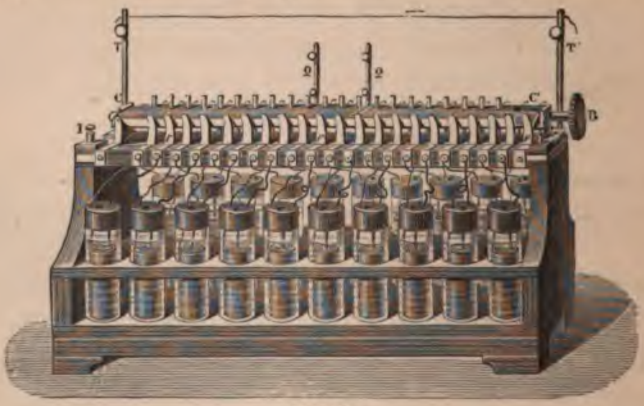


Fig. 220.

making this change of connections rapidly. A wooden roller, C C′, can be turned by means of a handle, B. Broad strips of

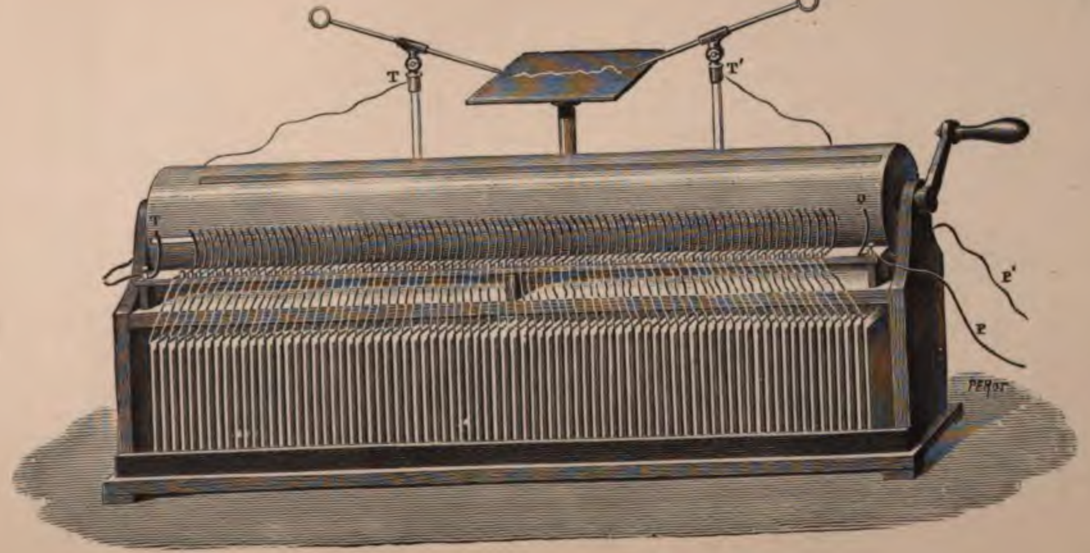


PLATE XLVII.—PLANTÉ'S RHEOSTATIC MACHINE.

copper (one of which is seen in front) are fixed along each side, and short copper rods (seen vertical) are fixed through the roller. For charging, the roller is turned as shown in figs. 220, 221, so that springs from all the negative poles press on one strip, and springs from all the positive poles press on the other.

Fig. 221.

Fig. 222.

To connect in series, the handle B is turned through 90°, so that each spring is connected by one of the copper rods to the one opposite to it, as seen in fig. 222. TT′ are the discharging poles for heating long wires, QQ′ those for heating shorter ones.

With a large secondary battery, consisting of 800 elements, some very fine luminous effects were obtained. It was charged by two Bunsen cells for several hours, and then discharged in the course of a few minutes. With a secondary battery of 200 elements a platinum wire $\frac{3}{10}$ to $\frac{4}{10}$ of a millim. diameter and 10 metres long was heated to redness.

Discharge in Vacuum Tubes.

A secondary battery of 800 elements will illuminate a vacuum tube of high "resistance" for $3\frac{1}{2}$ hours or more without recharging. The discharge was found to be beautifully stratified.*

Planté's Rheostatic Machine.—Plate XLVII.

The success of his experiments with secondary batteries led M. Planté to construct a *Rheostatic machine*† for converting voltaic electricity into electricity of high potential.

It consists of a number of mica and tinfoil condensers, and an arrangement exactly similar to that of the secondary battery for connecting the conductors in "side by side" for charging, and "in series" for discharge.

As it is possible to charge and discharge these condensers very rapidly, the handle is rotated continuously, and a continuous stream of sparks is obtained.

Plate XLVII. represents a large rheostatic machine containing 80 condensers. The cylinder at the top is 1 metre long and 15

* Planté, Tom. i., p. 259.

† Planté, Tom. i., p. 252; Tom. ii., p. 2.

centims. in diameter, and the machine gives sparks of 12 centims., or nearly 5 inches.

By experiments where only portions of the machine were used, M. Planté found that the length of spark was proportional to the number of condensers.

The length of spark increases as the number of elements in the charging battery is increased, and increases faster than the number of elements; but M. Planté was unable to determine the exact law of increase.

The rheostatic machine was charged by means of a battery of from 600 to 800 secondary elements, or by from 50 to 70 Bunsen cells. M. Planté did not find it to be of much practical use; but it is of considerable theoretical interest.

Rheostatic Machine for Quantity.*

M. Planté has also arranged a rheostatic machine for "quantity" effects. It, like the machine just described, has its condensers arranged "side by side" for charging by the secondary battery, but by a different arrangement of the commutator they are also discharged "side by side" instead of in series.

The commutator (figs. 223, 224) is arranged to give the con-

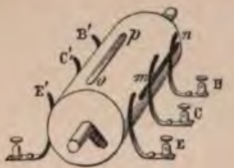


Fig. 223.

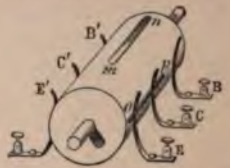


Fig. 224.

denser discharge "side by side" without mixture with the direct discharge of the secondary battery.

On an india-rubber cylinder are four strips of copper, each ⅔ the length of the cylinder, of which two, *m n* and *o p*, are seen in the figures.

Six springs, BCE, B′C′E′, press on the cylinder.

The pair BB′ are connected with the secondary battery, CC′ with the charging poles of a rheostatic machine (Plate XLVII.) whose commutator has been previously set in the position which connects its condensers "side by side." The discharge is taken from the springs EE′.

* Planté, ii. p. 23.

When the commutator is in the position shown in fig. 223, the battery is connected with the rheostatic machine and charges the condensers.

When it is in the position shown in fig. 224, the battery poles are insulated, and the condensers are connected to the discharging poles EE′.

When the cylinder is revolved rapidly, it gives an almost continuous series of discharges.

This commutator, instead of being revolved separately, is usually adapted to the machine itself (*a′ b′* fig. 225).

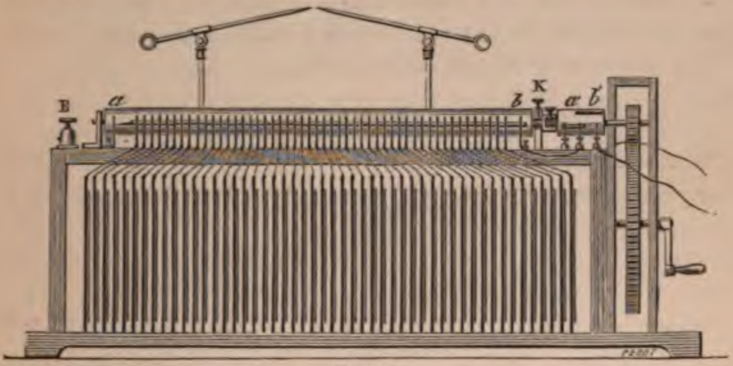


Fig. 225.

When it is desired to use the machine for "quantity," the pin K is raised, which disconnects the two cylinders and allows *a′b′* to revolve while *a b* remains at rest.

When it is desired to use the machine for "series" effects, K is pressed down, which connects the two cylinders and causes *a b* to revolve, and the machine to act in all respects like the machine previously described (page 145). Although the short cylinder *a′b′* also revolves, it does not then produce any effect.

Discharge of the "Quantity" Machine.

A series of brilliant sparks are obtained, but only of a length of from $\frac{2}{10}$ to $\frac{3}{10}$ millim., much shorter than the direct discharge of the secondary battery.

The spark, however, is much brighter and more violent than that of the direct discharge.

The difference between the discharges of the secondary battery with and without the quantity machine is closely analogous to

that between the discharge of an induction coil with and without a Leyden jar.*

Heating Effects.

The heating effect of the rheostatic machine is much greater when it is arranged for quantity than when it is arranged for series effects.

Mechanical Effects.

The mechanical effects of the quantity machine are very remarkable.

If the machine is connected to a voltameter, the passage of each spark through the conducting liquid is accompanied by a loud noise resembling a small explosion.

Nodes of Vibration in a Metallic Thread.

If the current of the "quantity" machine be sent through a fine platinum wire ($a\ b$ fig. 226) about $\frac{1}{20}$ millim. in diameter and

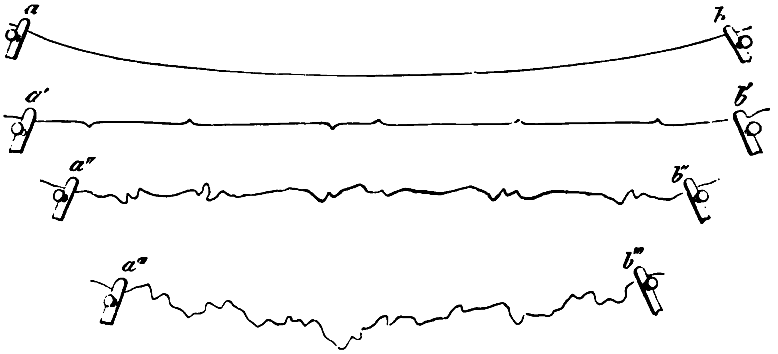


Fig. 226.

40 centims. (16 inches) long, it will be seen that a series of acute angles are formed at tolerably regular intervals all along the wire as in $a'b'$.

If the poles are brought nearer together so as to slacken the wire, fresh angles are formed, and the wire takes the shape $a''b''$.

If the length of the wire be reduced to about 10 centims. (4 inches), the current makes it white-hot, and it is twisted into the sharp angles $a'''b'''$, presenting the appearance of a continuous electric spark.

* Vol. ii. p. 53.

Noise.

The discharge through the wire is accompanied by a continuous crackling sound, very much like that of an electric spark, but produced in the wire itself.

Fragility of the Wire.

The wire becomes very brittle during the passage of the discharge. If the experiment lasts more than about two minutes, it breaks spontaneously.

Conclusion.

The following is the conclusion to which M. Planté considers these and other experiments (described in his book) to lead :—

"The phenomena which we have just described are of a nature to throw some light upon the mode of propagation of electricity. The molecular vibrations revealed by the nodes formed in the metal wire, by the noise observed in it, and by the notable change in its cohesion under the influence of the "dynamostatic" current, which we have just studied, ought to be produced in a less degree in conducting bodies traversed by electric currents of less tension. These vibrations would be too small to be perceptible, but they are none the less real.

"We may then conclude that the "electric movement" ought to propagate itself in bodies in the same manner as "mechanical movement," properly so called, by a series of very rapid vibrations of the more or less elastic matter which it traverses." *

* I do not myself express any opinion on this conclusion.

CHAPTER XL.

MAGNETO-ELECTRIC AND ELECTRO-MAGNETIC ENGINES.

Magneto-Electric Machines.

The fact that electric currents are produced in a wire when it moves in the neighbourhood of a magnet has been utilized in the construction of *magneto-electric* or *dynamo-electric* machines in which very powerful electric currents are produced by revolving coils of wire between the poles of large horse-shoe magnets. The motion is given either by hand or steam power.

The Siemens Armature.—Fig. 227.

In order to obtain the maximum effect, it is necessary that the

Fig. 227.

moving wires should cross the lines of magnetic force at right angles, and that the poles of the magnet between which the coil revolves should be as close together as possible.

To satisfy these two conditions, Mr. Siemens has invented the "armature" shown in fig. 227.

It consists of an axis which can be rapidly revolved, and on which a coil of wire is moved *longitudinally*. We see that this takes up but little room between the poles, and that the wires move to a great extent at right angles to the lines of force.

Alternate Currents.

Let A (fig. 228) represent a cross-section of one of the wires of the revolving coil, and suppose it to be moving round the centre O in the direction of the arrow between the poles SN of a horse-shoe magnet.

We see that, as long as it is to the right of the line EE′, it will be crossing the lines of force in one direction; and as long as it is to the left, it will be crossing them in the other direction.*

Fig. 228.

The current in the wire will therefore be reversed every half-revolution.

For some purposes these alternate currents are preferable to a continuous current.

When a continuous current is required, a "revolving commutator" is attached to the axis of revolution of the coil and collects the alternate currents, and sends them all in the same direction through the wire.

Practical Forms of the Machine.

An immense number of different forms of magneto-electric machines have been constructed. We shall now only describe one or two typical forms, referring the student for further details to treatises on Electric Lighting.†

The Hand Gramme Machine.—Fig. 229.

The small Gramme machine, shown in fig. 229, consists of a powerful steel magnet made up of a number of thin strips of steel magnetized separately and then bolted together.

The "armature" consists of an iron ring round whose circumference a number of separate coils of wire are wound so that the axis of each coil is tangential to the ring. Each coil is connected to the one opposite to it. A revolving commutator collects the currents of those coils which are moving across the lines of force, and delivers them all in the same direction to the wires leading from the machine.

The armature is revolved rapidly between the poles of the magnet by means of a multiplying wheel.

This sized machine produces about as much electricity as a pint-sized Grove cell, and gives a difference of potential depending on the speed at which it is worked.

It is usually supplied with two armatures—one wound with a short thick wire for "quantity" effects, the other with a long thin one for experiments where a large difference of potential is required.

* See vol. i. p. 288.

† See Du Moncel, "Sur l'Eclairage Électrique" (Paris, Hachette, 1879).

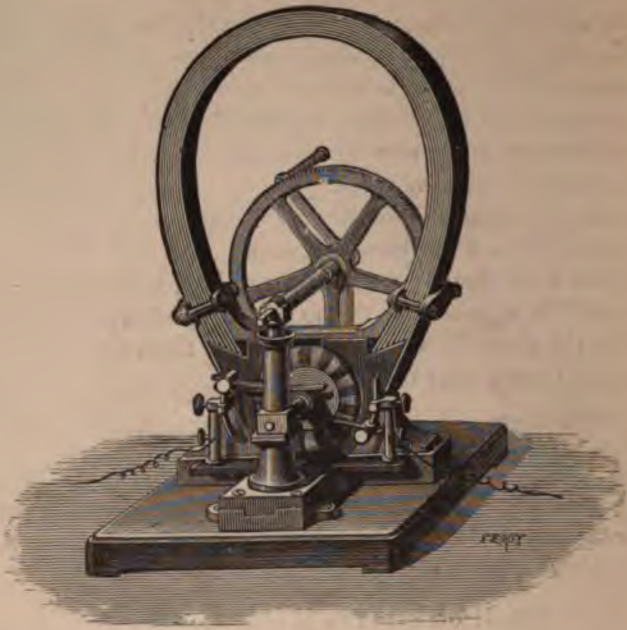


Fig. 229.

THE STEAM-POWER GRAMME MACHINE.—FIG. 230.

Fig. 230 represents a large Gramme machine intended for the production of a powerful electric light. It is driven by steam-power, and the armature revolves between the four poles of two very powerful *electro-magnets.*

The cores of these electro-magnets are of steel, and are magnetized once by a battery when the machine is constructed.

When the armature revolves, a feeble current is at first produced, but the connections are so arranged that the current on its way from the machine passes round the coils of the electro-magnets and increases their magnetism.

The magnets now act more powerfully on the revolving coil and cause a stronger current, which in its turn strengthens the magnets, and so the power of the machine goes on increasing indefinitely as the speed is increased.*

* This arrangement was first used in "Ladd's" dynamo-electric machine, brought out in 1867. It is, I believe, the invention of Mr. Tisley, who at that time was in Mr. Ladd's employment. See Proc. Roy. Soc., 1866-7, vol. XV. p. 404.

As the current gets stronger, the resistance, which we know by Lenz's law,* that it opposes to the motion of the wire gets greater, and so a limit to the speed is reached which depends on the power of the steam-engine employed to drive the machine.†

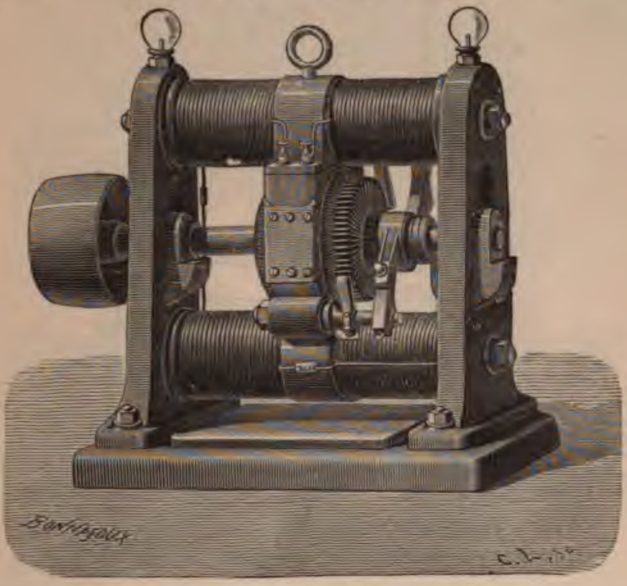


Fig. 230.

The revolving commutator is the same as in the hand machine. In both forms the direction of the currents reverses when the direction of revolution is reversed.

The large machine stands about 2 feet 6 in. high.

De Meritens' Machine.—Fig. 231.

Fig. 231 represents an arrangement now a good deal used, and invented by M. de Meritens. The coils are arranged round the circumference of a large revolving wheel, outside which are fixed a number of powerful steel magnets.

It gives rapidly alternating currents, the current in each coil being reversed as it passes from the north to the south pole of any one of the magnets.

* Vol. i. p. 319.

† In actual work, there is a limit of advantageous speed for each machine depending on the amount of mechanical friction and strain on the bearings, &c.

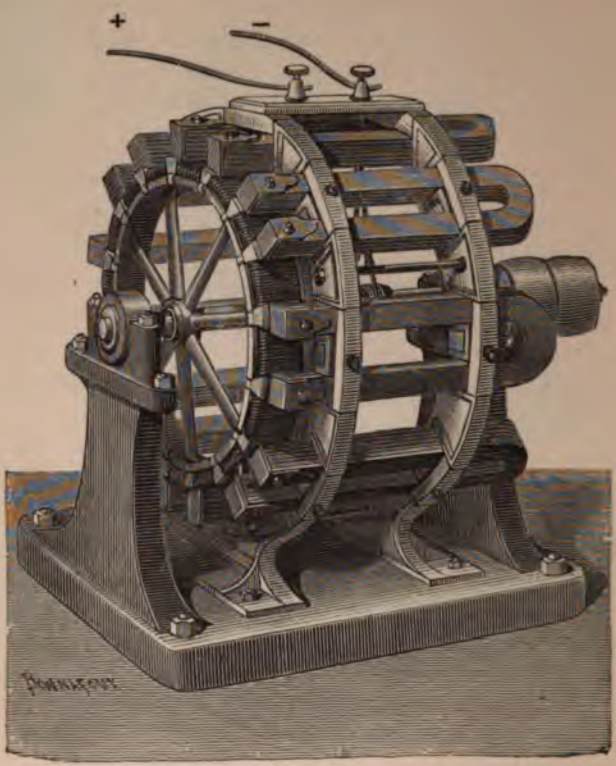


Fig. 231.

A commutator can be attached when direct currents are required.

ELECTRO-MAGNETIC ENGINES.

Electric currents can be used to drive small engines. These "electro-magnetic" engines, as they are called, are extremely useful for laboratory work, for driving rapid commutators, revolving mirrors, &c., as they can be worked at great speed, and started and stopped instantly, and, moreover, do not require watching when they are at work.

The large cost of the zinc consumed in the battery as compared to the coal consumed in a steam-engine of equal power prohibits their employment on a large scale.

The rapid break shown in Plate XXXIII. (vol. ii. p. 49) is driven by a small electro-magnetic engine.

This engine, which is made by Mr. Apps, is of particularly good construction for high-speed work. Two horse-shoe electro-magnets are placed with their poles facing each other. One is fixed and the other revolves round an axis which is parallel to the cores, and half-way between them. The current in the fixed magnet has a constant direction, that in the revolving magnet is reversed every half-revolution. The commutator is so arranged that the force between poles which are approaching each other is always attractive, and that between receding poles repulsive. Two screws regulate the pressure of the commutator springs.

With a little care as to the adjustment, it was found possible to drive this engine at a speed of 100 revolutions a second.

The fly-wheel of the engine is just two inches in diameter.

Reversibility of Gramme's Machine.

If the current from a battery be sent through the wires of a Gramme machine, the armature will revolve, and the machine can be employed to drive a lathe or do other mechanical work.

Electric Transmission of Power.

Mechanical power can be conveniently and economically transmitted, say from a water-wheel, to a factory at a distance by means of two magneto-electric, or as they are called "Dynamo," machines, either of the Gramme form or of some other construction.

One being driven by the water power, the electric currents produced are carried through wires which may possibly be a mile long, and cause the second machine, placed in the factory, to revolve and drive lathes, and do other mechanical work.*

* See "The Electric Transmission of Mechanical Power." A Lecture delivered to the working men at Sheffield, during the British Association Meeting in that town, in 1879, by Professor W. E. Ayrton. "Electrician," August 30, 1879.

CHAPTER XLI.

THE ELECTRIC LIGHT.

When a sufficiently powerful current of electricity is sent through two points of gas carbon placed in contact, they may, after the current has commenced, be separated to a distance of several millims. without interrupting the current.

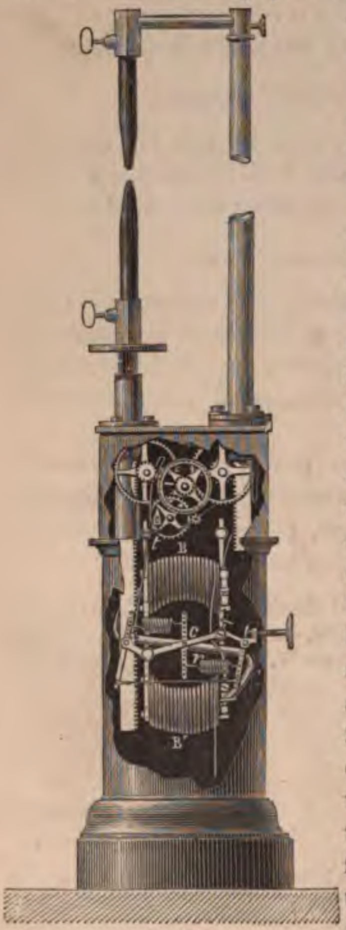


Fig. 232.

When this is done, a brilliant light is produced at the point of separation. As the light continues, the carbons become slightly worn away, and therefore the distance increases. In order that the distance may not become too great to allow the current to pass, the carbons must be moved nearer together. This is effected in several ways. In most forms of regulator, clockwork moves the carbons towards each other, but is generally prevented from acting by a break worked by an electro-magnet, BB′ (fig. 232) through whose coils the current passes. As soon as, by the increase of distance between the carbons, the current is enfeebled, the electro-magnet releases the clockwork, and the carbons move towards each other until the

current is sufficiently strengthened to cause the magnetic break to again come into action.

It is found that the (+) carbon wears away more quickly than the (−) one; and therefore, in order to keep the light in the same place, it is necessary that the former should be moved more than the latter.

In the clock instruments this is managed by making the cog-wheels, which gear respectively into the rack-works of the two carbons, of different sizes. An immense number of other regulators have been invented, descriptions of which will be found in treatises on Electric Lighting.

The smallest battery which will produce a light at all is ten cells of Grove; for all lecture purposes forty or more are used.

Powerful lights are, however, better produced by a "dynamo" machine. The lights shown in many of the lighthouses on the English coast are produced each by a "dynamo" machine driven by a powerful steam-engine.

Fig. 233.

When a machine giving alternating currents is used, the arrangement for moving the carbons unequally is not required.

In lamps such as are used in lectures, the carbon points are about $\frac{1}{8}$ in. (3 mm.) square. In the larger machines, however, the carbons are much larger.

THE JABLOCHKOFF CANDLE.—FIG. 233.

M. Jablochkoff has invented a "candle" consisting of two carbon rods BB′ (fig. 233) laid side by side, separated by a layer of kaolin or china clay. The current goes up one carbon and down the other, going across from one to the other at the top, where it forms the arc and the light. The carbons and clay burn away together.

Several candles are usually placed in one lamp, and an automatic arrangement is provided (M O, *m f*, fig. 233) such that, when one candle is nearly burnt out, a spring is released and the current is transferred to a fresh one.

CHAPTER XLII.

RELATIONS BETWEEN ELECTRICITY AND HEAT.

Heating Effect of the Electric Current.

Currents heat the wires in which they pass. The heating effect of a current is proportional to

1. The resistance of the conductor;
2. The square of the strength of the current;
3. The time during which the current lasts.

The total amount of mechanical work done by a current C, in overcoming a resistance R, for a time t, is

$$R\,C^2\,t.$$

The amount of heat to which this is equivalent is found, by dividing it by J, the mechanical equivalent of heat;* and then we have, when the whole current is converted into a quantity of heat H—

$$H = \frac{R\,C^2\,t}{J}.$$

Thermo-Electricity.

When two metals are soldered together so as to form a closed circuit, fig. 234, and one of the junctions is heated more than the other, an electric current is formed in the circuit. The direction of the current depends on the nature of the metals, and under certain conditions upon the temperature.

Fig. 234.

The strength of the current for a given temperature and difference of temperature is different with different metals. The relation of the strength and direction of currents, in different pairs, obeys the following law:—

Let there be three metals A B C, such that if A and B be soldered together, the current across the heated junction will be from A to B, and also such that, if B and C be soldered together,

* See Tyndall, "Heat a Mode of Motion" (Longmans), 4th ed., p. 72 art. 84.

the current across the heated junction will be from B to C. Then experiment shows that, if A and C be soldered together, the current across the heated junction will be from A to C, and that its strength will be equal to the sums of currents between A B and B C.*

Thermo-Electric Scale.

It has been found possible to construct a Thermo-Electric Scale—that is, a list of metals arranged in such an order that, if any two be soldered together, the current across the heated junction will be from the metal higher in the list, to that lower; and that the current between any two metals is always greater than that between any other two, the position of both of which in the list is between the two first.

The following is a Thermo-Electric Scale given by Becquerel:†

Bismuth.
Platinum.
Lead.
Tin.
Copper.
Gold.
Silver.
Zinc.
Iron.
Antimony.

Thus we see that the strongest current is obtained by a couple of bismuth and antimony, and these two metals are therefore used for the construction of *Thermo-Electric Piles.*

The Thermo-Electric Pile.

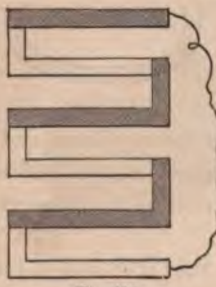


Fig. 235.

With one piece of each metal only a feeble current is produced.

When a more powerful current is required, it is found possible to combine the effects of a number of separate pairs.

Thus, if the shaded bars in fig. 235 represent antimony, and the plain ones bismuth, we shall see that, if all the junctions on one side are heated, we shall

* I give this law on the authority of M. Mascart. It is stated in his *Électricité Statique*, T. ii. p. 427. He there says that it was discovered by Becquerel, but gives no reference.

† *Ann. de Chimie,* 2nd Series, T. xli. p. 353.

obtain, in a wire joining the poles, the sum of all the currents produced in each respectively.

This is the arrangement of the thermo-electric pile, which is often made of several hundred couples, and with a sensitive galvanometer is by far the most delicate thermometer known.

Fig. 236.

Fig. 236 represents the usual form in which the pile is made. A conical reflector can be placed on one end to concentrate heat on the face of the pile.

The thermo-electric currents have very small electro-motive force, and hence galvanometers for their measurement should have short thick wire.

Reversal of the Current.

In 1823, Cumming discovered that, if the temperature of one junction of certain thermo-electric circuits was raised above a certain point, the current in them was reversed.

In a circuit of copper and iron, if one junction be kept at the ordinary temperature, and the other be heated, the electro-motive force continues to increase till the hot junction has reached a témperature of about 284° C. When the temperature is raised still further, the electro-motive force first decreases and is finally reversed.

At a certain temperature T, the two metals are neutral to each other. For iron and copper, T is, as we have said, about 284° C.

The reversal of the current may be obtained more easily by heating the colder junction. When the temperature of both junctions is above T, the current sets from iron to copper through the hotter junction—that is to say, in the reverse direction to that in which it flows when both are below T.*

Electro-motive Force.

Professor Tait has investigated the electro-motive force of thermo-electric circuits of different metals, and at different temperatures. He finds that the electro-motive force of a circuit may be expressed very accurately by the formula—

* Maxwell's "Electricity," 252, vol. i. p. 304.

$$E = a(t_1 - t_2)[t_0 - \tfrac{1}{2}(t_1 + t_2)]$$

where t_1 is the absolute temperature* of the hot junction, t_2 that of the cold junction; and t_0 the temperature when the two metals are neutral to each other. a is a co-efficient, depending on the nature of the metals.†

Peltier's Phenomenon.

Peltier discovered that the thermo-electric effect is "reversible" —that is, that when a current is sent across the junction of two metals, the junction is heated when the current is in one direction, and cooled when it is in the other.

It must be remembered that a current always heats any conductor through which it passes. The fact that the heating due to ordinary resistance is independent of the direction of the current, and that the Peltier effect is not, enables us to measure the latter, for in one case the heating will be that due to resistance plus the heating effect of the Peltier, and in the other that due to resistance minus the cooling effect of the Peltier. The cooling due to the Peltier effect will then be half the difference of the heating effects of the currents in the two directions.

The total heat absorbed at the junction of the two metals from a current C in a time t will be

$$\Pi \, Ct$$

where Π is the co-efficient of the Peltier effect for the given metals —that is, the quantity of heat absorbed at the junction from unit current in unit time, for the heat absorbed is proportional to the strength of the current and to the time during which it lasts. The heat *generated* at the junction may then be written

$$-\Pi \, Ct,$$

for heat absorbed may be considered to be negative heat generated.

The heating effect due to resistance is by page 159

$$\frac{R}{J} C^2 t.$$

* For an explanation of what is meant by "absolute temperature," see Maxwell's "Theory of Heat" (Longmans), 4th ed. p. 159.

† Maxwell's "Electricity," 254, vol. i. p. 305.

The total heat generated in the compound circuit is then

$$H_1 = \frac{R}{J} \quad C^2t - \Pi \, Ct.*$$

That is, with the current in the direction which produces cooling in the junction, the total heating effect is less than if only the resistance acted.

Let the current be reversed. We know by experiment that the total heating effect will now be greater than that due only to resistance. In the equation, this reversal of the current is expressed by changing the sign of C; that is, writing—C for C and we have—

$$H_2 = \frac{R}{J} (-C)^2t - \Pi \, (-C) \, t,$$

but $(-C)^2 = C^2$ and therefore reversing the current makes no change in the first term, while it changes the sign of the second, and we have—

$$H_2 = \frac{R}{J} C^2t + \Pi \, Ct.$$

The total Peltier effect is then

$$\tfrac{1}{2} (H_2 - H_1),$$

and the unit Peltier effect for those metals is

$$\Pi = \tfrac{1}{2} \frac{H_2 - H_1}{Ct}.$$

To determine experimentally the unit Peltier effect (Π) for any two metals, we have then to solder them together and measure the quantities of heat produced by sending a known current for a known time, first in one direction and then in the other, and then to divide half the difference of the two quantities by the product of the current into the time.

The quantities of heat can be measured by immersing the junction in a known quantity of a liquid of known specific heat and noting the increase of temperature.

We observe that it is not necessary to know the resistance of the wires.

Pyro-Electricity.

It is found, when a crystal of tourmaline is heated, that its two ends become oppositely electrified.

* Maxwell's "Electricity," 249, vol. i. p. 300.

The phenomena of "Pyro-electricity," as it is called, have been studied by M. Gaugain.*

M. Gaugain has shown that a tourmaline crystal, when heated, may be considered as a voltaic cell of high electro-motive force and high internal resistance. On connecting the ends of a crystal by a wire, a current of electricity is obtained on heating the crystal.

The electro-motive force of different portions of the same crystal is proportional to its length, and the currents produced vary with the mean cross-section—that is, inversely as the resistance.

In 1759† Bergmann showed that the total quantities of (+) and (−) electricities produced are always equal, for their algebraic sum is zero.

This was proved by placing a crystal of tourmaline in hot water in an insulated metal vessel connected to an electroscope. It was found that no deflection was produced.

The polarity of tourmaline does not depend on the temperature but on the variation of it.

If a tourmaline AB be heated, it will be found that one end, A, is (+) and the other, B, is (−).

Let now the crystal be discharged by touching its ends with the fingers. It will be no longer electrified.

If it be now allowed to cool to its original temperature, the end B will become (+) and A will become (−).

* "Ann. de Chem. et Phys.," 3e ser. t. lvii. p. 5, and Mascart, "Electricité Statique," t. ii. p. 497.

† Phil. Trans. 1759, p. 403.

CHAPTER XLIII.

ELECTRICITY OF CONTACT.

When two different metals are in contact, there is, in general, an electro-motive force acting across the junction from the one to the other.

For instance, if a piece of copper and a piece of zinc be soldered together, the zinc will be found to be positive as compared with the copper. Volta's theory of contact electricity is based on this fact.

This electro-motive force cannot in general produce a current, for to form a closed circuit of the two metals, two junctions are necessary, and the electro-motive forces at the two junctions will be equal and opposite. It is found that the insertion of an intermediate metal does not destroy the balance, for the following law holds:—

Let A B C be any three metals* arranged in circuit

then the junctions are A B, B C, C A, and the electro-motive forces at them may be written

$$F_{A\,B},\ F_{B\,C},\ F_{C\,A};$$

then always we shall have, if A, B, and C are at the same temperature,

$$F_{A\,B} + F_{B\,C} + F_{C\,A} = 0;$$

or, the electro-motive force between A and B is equal and opposite to the sum of the electro-motive forces between B and C and C and A, and the same is true for any number of metals in circuit. It is obvious that if this were not so, the law of the conservation of energy would not hold; for we could obtain a current without chemical or mechanical action.

The neglect of this limitation led Volta and his followers into

* C may be the wire of a galvanometer.

such absurdities, that Faraday was induced to deny the existence of contact electricity altogether.

A large portion of the second volume of his "Experimental Researches" is devoted to proving that all cases of supposed electrification by contact can be shown to be due to either chemical or mechanical action.

Faraday's mistake is easily explained. The electrometer of his day (1839) being a very untrustworthy instrument, he used a galvanometer, which would not show the existence of a simple difference of potential, but only that constant renewing of the difference which we call current. In all these cases he rightly said that the effects observed could always be traced to some chemical or mechanical cause. It is now well known that, *though contact produces a difference of potential, this difference of potential only produces a current when some extraneous means are employed to keep it constantly renewed.*

In the Voltaic battery, according to Volta's theory, the action of the liquid is to reduce the two metals to the same potential.

The difference of potential being at once renewed at the junction, a continuous current is kept up at the expense of the chemical action between the liquid and one of the metals.

Professor Maxwell quotes this theory* without expressing any opinion about it. Sir Wm. Thomson,† however, says, "For nearly two years I have felt sure that the proper explanation of Voltaic action in the common Voltaic arrangement is very near Volta's . . . . I now think it is quite certain that two metals, dipped in one electrolytic liquid, will (when polarization is done away with) reduce two dry pieces of the same metals, when connected each to each by metallic arcs, to the same potential."

Instead of equalizing the potentials chemically, we may do it mechanically, as has been done by Sir Wm. Thomson.‡

A copper funnel is fixed into an insulated zinc tube, as shown in fig. 237. The contact between the copper and zinc produces a difference of potential. Copper filings placed in the funnel

* "Electricity," 247, vol. i. p. 300.

† "Proceedings Lit. and Phil. Soc. of Manchester," Jan. 21, 1862, and "Papers on Electro-statics," p. 318.

‡ Proc. Roy. Soc., 1867, vol. xvi. p. 71, and "Papers on Electro-statics," p. 324.

acquire the same potential as the funnel, and therefore their potential differs from that of the zinc tube. They are allowed to stream out through the tube without touching it. Each as it falls becomes negatively electrified by induction, and they produce a rapidly increasing negative charge on a small insulated can, placed to catch them. Now, if the can be connected to earth by a wire, a current will flow through that wire as long as the stream of filings continues. In this case the difference of potential is undoubtedly caused by contact, but the energy required to convert this difference of potential into current is supplied by the work done by gravity on the falling filings.

Fig. 237.

On June 15th, 1876, Messrs. Hugo Müller* and Warren De La Rue communicated to the Royal Society an account of an apparatus where the energy required to enable the electrification of contact to produce a current was obtained by a piece of mechanism which "brings together and separates two discs, one of copper and one of zinc, each six inches diameter, 400 times in a minute, and after each separation makes the zinc plate touch a spring attached to an insulated conductor; and, moreover, by means of cams, makes earth connection with either disc, or with both, previous to their being brought again into contact."

They found that when the apparatus was making 320 breaks a minute, the tension of the electricity as compared to that of a chloride of silver cell was as

30·88 to 1,

that is, that when the machine was connected to the electrometer, the deflection was nearly equal to that which would have been produced by 31 cells in series.

A feeble current was obtained when the electricity was led to earth through a reflecting galvanometer; it gave 35 divisions of the scale, or about $\frac{1}{140}$ part of that produced by $\frac{1}{2}$-inch bits of copper and zinc wire, held one in the right hand and one in the left between dry fingers.

Mr. Joseph Thomson† states that he has found that if cakes

* Proc. Roy. Soc., 1876, vol. xxv. p. 258.
† Ibid., June 15, 1876, vol. xxv. p. 169.

be made, each of two insulating substances, and the electrified needle of an electrometer be suspended over them along their line of separation, it will be deflected, showing a difference of potential between them.

He has found that, in the following cakes, the substance first mentioned becomes (+), the second (−).

(+)		(−)
Glass	and	wax,
Glass	"	resin,
Glass	"	sulphur,
Glass	"	solid paraffin,
Zinc	"	sulphur,
Sulphur	"	ebonite.

He observes :—

"The series so far, being in the same order as the frictional series, seems to suggest that the electrical displacement which takes place when two non-conductors are put in contact, acts as a predisposing cause, in virtue of which the work done in rubbing them together is converted into electrical separation."

Numerous other experiments have been made, but without decided results up to 1876.

Experiments of Ayrton and Perry.—Plate XLVIII.

At the meeting of the British Association in 1876, Professors Ayrton and Perry communicated a preliminary notice of a series of experiments they had made to determine whether in a galvanic cell—for example, a Daniell's, Grove's, &c.—the electromotive force of the cell was, or was not, equal to the algebraical sum of all the differences of potential, each being measured separately, at the various contacts of dissimilar substances in the cell. A further account of the investigation appeared subsequently in Parts I. and II. of the "Contact Theory of Voltaic Action,"* and the experiments were fully described, by which the following law was proved :—

"The electro-motive force of contact of two metals or two electrolytes, or of a metal and an electrolyte, is in each case a constant for the same temperature and in the same gas; that is to say, if AB means the electro-motive force of contact of the metal or electrolyte A, and the metal or electrolyte B (measured when A and B are not in contact with other conducting substances), AB being identical with −BA; then the total electro-motive force of any

* Proc. Roy. Soc., vol. xxvii., 1878, p. 196.

closed heterogeneous circuit composed of the substances A, B, C, N is:

$$AB + BC + \&c.\ MN + NA."$$

They go on to say:—"The proof of this law was very important, as it was generally thought not to hold true."

"For example, Professor F. Jenkin, in the edition of his 'Electricity and Magnetism' of 1873, said, on page 44:—'The following series of phenomena occur when metals and an electrolyte are placed in contact:—1. When a single metal is placed in contact with an electrolyte, a definite difference of potentials is produced between the liquid and the metal. If zinc be plunged in water, the zinc becomes negative, the water positive. Copper plunged in water also becomes negative, but much less so than zinc. 2. If two metals be plunged in water (as copper and zinc), the copper, the zinc, and the water forming a galvanic cell, all remain at one potential, and no charge of electricity is observed on any part of the system."

If *all* the substances A, B, C, &c., N are metals, then

$$AB + BC + \&c. + MN = AN;$$

but if one or more of them be electrolytes, solid or liquid, then Prof. Ayrton and Perry's experiments show that the difference of potential between A and N when joined by B, C, &c., is equal to

$$AB + BC + \&c. + MN;$$

but we cannot from this sum predict the value of AN, the difference of potentials between A and N when joined *directly*, since the difference of potentials *depends on the path taken* in going from one body to another when electrolytes are in question.

In Messrs. Ayrton and Perry's experiments an *Induction* method was used which got rid of all the difficulties caused by the *contact* of the substances under examination with the poles of the electrometer.

The method of measurement was as follows:—Let 3 and 4 (fig. 238) be two insulated gilt-brass plates connected with the electrodes of a delicate quadrant electrometer. Let 1 under 3 and 2 under 4 be the surfaces whose contact difference of potential is to be measured. 3 and 4 are first connected together and then insulated, but remain connected with their respective electrometer quadrants. Now, 1 and 2 are made to change places with one another,

Fig. 238.

1 being now under 4 and 2 under 3, then the deflection of the electrometer needle will give a measure of the difference of potentials between 1 and 2. And it is shown theoretically that "the difference of potentials d observed with the electrometer will be proportional to the difference of potentials a that we desire to measure, provided the induction arrangement is symmetrical in both positions, or provided that A, B, and D be each nought, where A and A + a are the differences of potential of 1 and 2, B the common potential of 3 and 4 before reversal, and D and D + d their respective potentials after reversal. Perfect symmetry in the apparatus being impossible, the latter condition was always experimentally fulfilled."

The actual apparatus used in 1876 somewhat improved for the subsequent investigation, and described by the authors in their paper No. III. of 1879,* is shown in Plate XLVIII.

The substances of which the contact difference of potential are to be measured are carried on a table, AB.

In Plate XLVIII. a liquid, L, and a solid plate, P, of about 530 sq. centims. area are shown in position. The table AB is levelled by three screws, $l\,l$, and carried on three brass wheels, W, which run on a circular very rigid metallic railway, R. To avoid lateral motion the table is kept centred by a stout iron pin M, turning in a brass socket S.

In order to rotate the lower substances, 1 and 2, it is necessary, if one or both of them be a liquid, first to increase the distance between 1, 2 and 3, 4 in order that 3 and 4 may not strike against the sides of the vessel carrying the liquid.

This was done by raising and lowering the upper plates, 3, 4, by means of the "parallel ruler motion" shown in Plate XLVIII.

The upper framework is lifted by the rod $r\,r$, which has a cross-piece $p\,p$, which can either be lowered through the slot $s\,s$, or by turning the rod $r\,r$ caused to rest across it.

The upper plates are supported by clean glass rods G, which are kept dry by sulphuric acid in the lead cups U.

The whole apparatus, including the short circuit key and electrometer, was, to avoid induction from outside, enclosed in a large zinc case connected with the earth, and was not opened at all during one complete experiment, consisting of some ten short circuitings of the upper plates, reversals of the table AB, and corresponding readings to the right and left of the electrometer needle.

* Phil. Trans., 1880, p. 15.

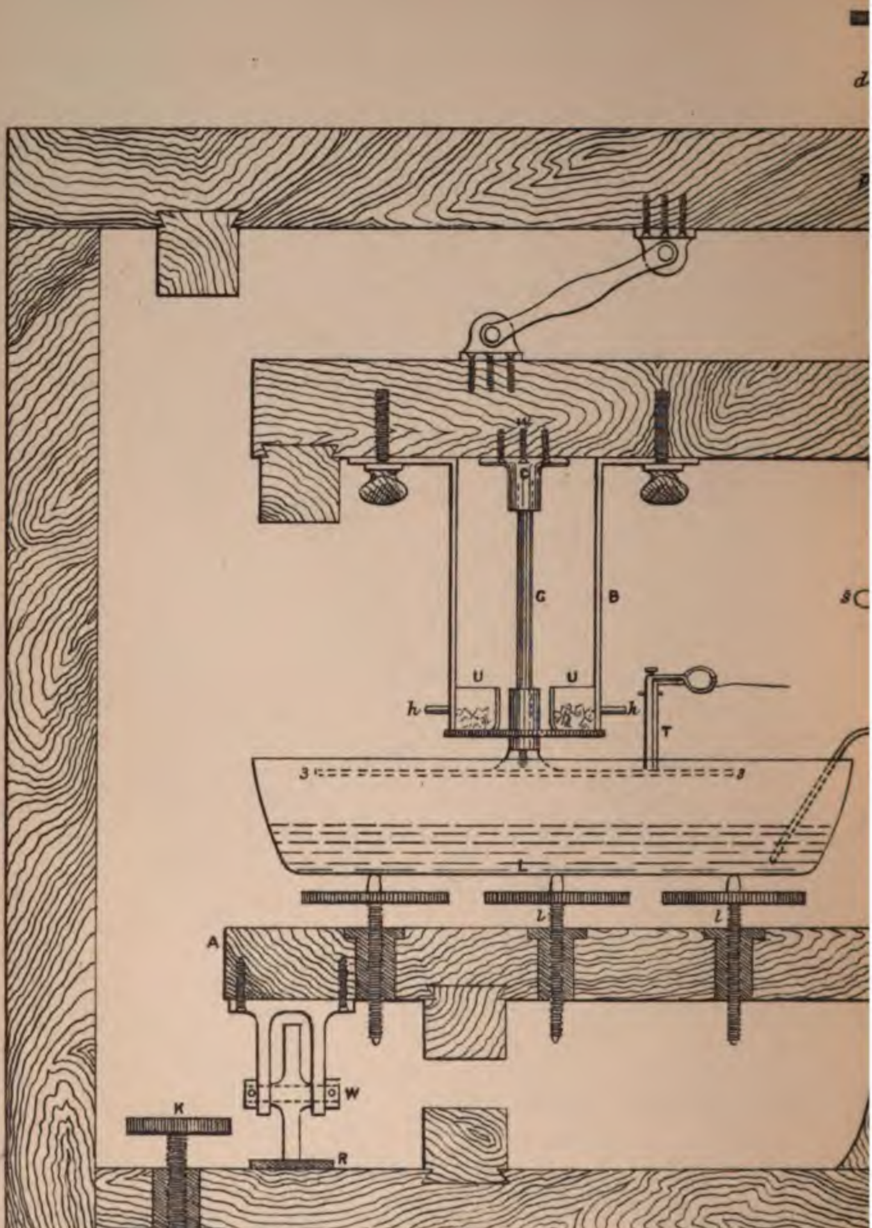
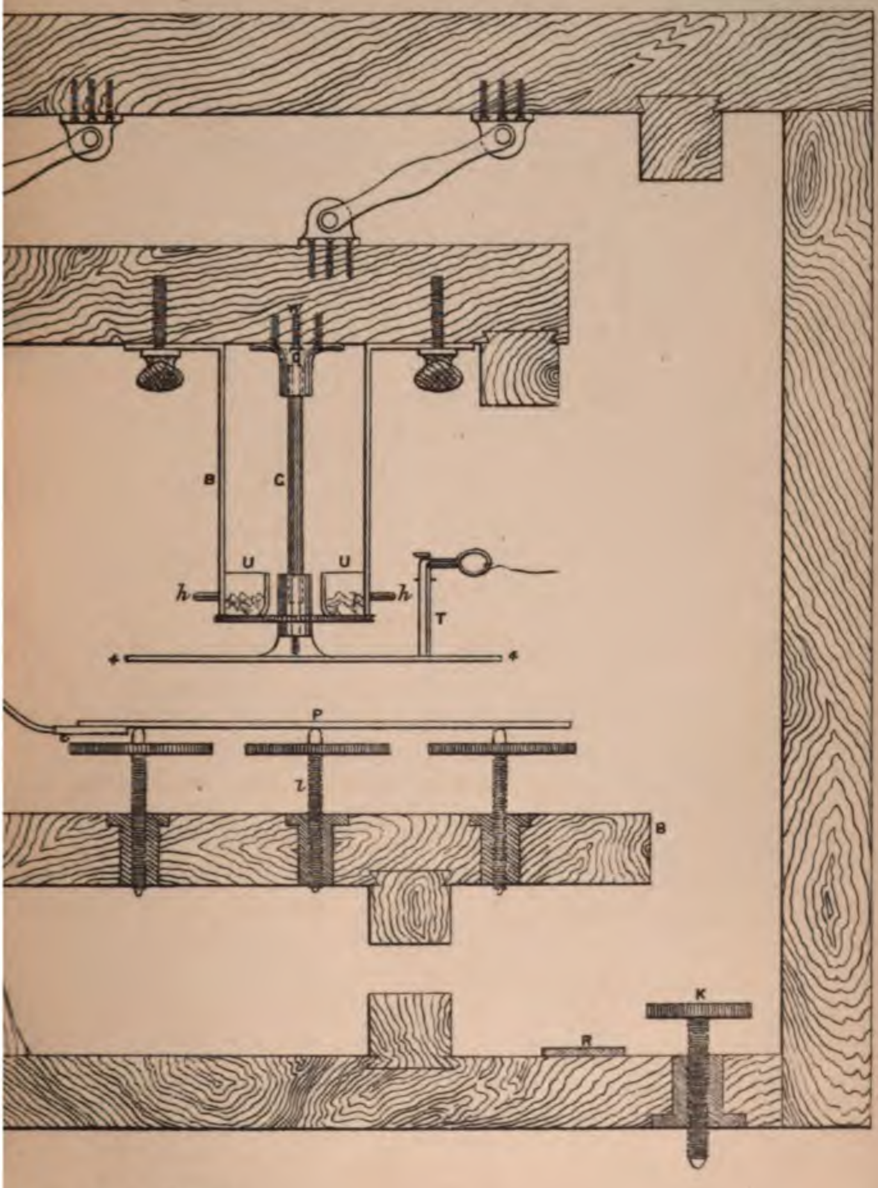


Plate XLVIII.

Contact Electrica

$\frac{4}{15}$ of full size.



rton and Perry

The following is a complete operation to obtain the contact difference of potentials, between a metal and liquid, for example. Suppose the permanent adjustments to have been made, and the gilt plates 3 and 4 are quite bright. The plate P is cleaned with emery paper that has touched *no other metal*, and all traces of the emery removed by means of a clean dry cloth; it is then placed on the three levelling screws *l*, and fixed in position by hole, slot, and plane.* The porcelain dish containing the liquid is laid in a metal one just fitting it, and on the base of which is a hole, slot, and plane; this is now laid on the other levelling screws *l*.

The rod *r r* is then lowered until the disk *d d* rests on a brass plate let into the top of the wooden framework at the top of the instrument—that is, until the induction plates 3 and 4 are in their lowest position. The levelling screws *l l* are now raised until a small metal ball, of a diameter of eight millims., is in contact at three fixed points with the plate 4 and the plate P, or until, when in contact with the plate 3, it and its reflection in the liquid L appear to meet. To avoid any harm arising from possible contact of the liquid with this gauge ball, it was made of a material not acted on by the particular liquid under experiment.

Before proceeding further, each pair of quadrants is in succession put to earth, the other pair remaining insulated in order to test for any possible leakage from the needles to the quadrants. Each pair of quadrants is now charged with a battery, the other pair being connected with the earth, in order to test for any leakage along the glass rods G, the small glass rods supporting the quadrants in the electrometer, or along the paraffined ebonite pillars of the short circuiting key. It having thus been ascertained that there is no leakage, the strip of metal which has been cut from the same sheet of metal as P itself, and temporarily attached to it by a binding screw soldered to P, is made quite bright with emery paper and a cloth, and its end is dipped into the liquid L, as shown in Plate XLVIII., fig. 4. The zinc case is then closed up, plates 3 and 4 connected together, and with the earth, by means of a key (the handle of which was a long

* "Hole, slot, and plane." This is an arrangement invented by Sir Wm. Thomson to allow any apparatus supported on three feet to be removed from a table and replaced exactly in the same position. Let 1, 2, 3 be the feet; 1 is placed in a small *hole* made in the table; 2 in a short *slot* whose direction if produced would pass through the hole; 3 rests on the *plane* surface of the table.

thin ebonite rod projecting through the zinc case), and the electrometer reading taken. 3 and 4 are then insulated from one another, and from the earth, and raised by means of the rod *r r* projecting above through the zinc case; the table A B is turned from below by means of a handle passing through the base of the instrument; 3 and 4 are then lowered into exactly their former position, this being ensured by the parallel motion of the supporting beam and by the limiting stop, *d d*. The reading of the electrometer is now taken. Then the processes of "short circuit, insulate, raise, reverse, and lower, and take a new electrometer reading, &c.," are repeated.

Some ten readings having thus been obtained, a fresh set of experiments is always made with the same two substances in the following way in order to compensate for the error introduced by defects in parallelism of the apparatus affecting the result obtained from two rigid surfaces (as those of copper and zinc), differently from the result found with one or with two liquid surfaces under examination. Instead of commencing, as before, with the liquid L under 3 and the plate P under 4, the experimenters start with the plate under 3 and the liquid under 4, and readjust, by means of the levelling screws *l*, the heights of the surfaces, until their distance from the plates 3 and 4 is, as before, 8 millims. They then short circuit, insulate, raise, reverse, and lower, and take exactly as many readings as before; and the mean of the two sets of readings, obtained with the two modes of levelling, is regarded as the result of the particular experiment.

"To test the accuracy of the statement, quoted on page 169 from Professor Jenkin's 'Electricity,' that when copper and zinc are both plunged into water they are all at the same potential, the following sets of experiments were made. The plates 1 and 2 (fig. 238) were respectively zinc and copper, and they were connected together by means of a liquid in a small beaker having no direct inductive action on the plates 3 and 4. First, however, the apparatus was calibrated thus:—

"TABLE VIII.—13th April, 1876. Plates 10 mm. apart.
Latimer Clark's Standard Cell.

Zero.	Reading.	Deflection.
955·0	892·0	63·0
954·5	1018·5	64·0
954·5	891·8	62·7
953·1	1017·1	64·0

Mean . . . 63·4
Assumed to be 1·457 volts.
Direct reading is 355

Therefore ratio is $\frac{355}{63 \cdot 4}$ or 5·6.

Experiments :—

" Zinc and copper connected by distilled water at 17° C. Zinc is negative to copper.

Zero.	Reading.	Deflection.
953	960·2	7·2
952	947·0	5·0
952	960·0	8·0
952	946·5	5·5
951·9	961·0	9·1
952	945·0	7·0
952	961·0	9·0
952·9	946·2	6·7

An interval of 15 minutes.

953	961·0	8·0
952·8	945·1	7.7

Mean . . 7·32 or 0·168 volts.

" Zinc and copper metallically connected. Zinc positive to copper.

Zero.	Reading.	Deflection.
953·0	926.0	27·0
952·7	990·0	37·3
951·0	920·3	30·7
950·1	985·1	35·0
950·0	919·5	30·5
950·2	984·6	34·4
951·0	918·0	33·0
951·1	985·2	34·1

Mean . . 32·7 or 0·751 volts.

" Zinc and copper connected by saturated pure zinc sulphate at 17° C. Zinc negative to copper.

Zero.	Reading.	Deflection.
952·0	961·5	9·5
951·9	944·2	7·7
951·8	960·0	8·2
951·9	943·1	8·8
952·0	960·0	8·0
952·1	944·6	7·5

Interval of 10 minutes.

953·1	960·0	6·9
953·2	945·0	8·2
953·1	961·2	8·1
953·3	945·2	8·1
953·7	961·0	7·3
953·9	945·2	8·7
Mean of first six	. .	8·3 or 0·191 volts.
Mean of last six	. .	7·9 or 0·182 volts.

"From these experiments it followed that the above statement made in text-books, and which was based on certain experiments of Sir William Thomson, is only approximately correct."

From Professor Ayrton and Perry's experiments, and from those previously made by Sir William Thomson, they were led to conclude "that, when zinc and copper are immersed in water, there are three successive states to be noticed. At the instant of immersion the zinc and copper may possibly be reduced to the same potential, so that the electro-motive force of the voltaic cell E is equal to the difference of potential ZC between zinc and copper in contact; the zinc now becomes negative to the copper, so that E reaches a limit which is greater than ZC; lastly, if a current be allowed to pass by metallically connecting the zinc and copper, polarization occurs and the zinc becomes gradually less negative to the copper, E diminishing, therefore, from its maximum value. But when a saturated solution of zinc sulphate is employed instead of water, the first state, if it exists at all, exists for so short a time that practically zinc and copper in zinc sulphate are never at the same potential. Thus when care is taken to keep the zinc and copper in a water cell well insulated from one another, E is found to increase from a value very little greater than ZC, the electro-motive force of contact of zinc and copper, to a limit, but in a zinc sulphate cell no such great increase is observed."

Subsequently the difference of potentials of a number of single contacts of dissimilar substances were measured, as well as the electro-motive forces of complete and incomplete cells built up with the *very same specimens* of the materials immediately after the previous tests were made. The following are some of the results obtained:—Let C, Z, and L represent the copper, zinc, and liquid respectively of a simple cell let L_1 and L_2 be the

liquid in contact with the copper, and the liquid in contact with the zinc of a Daniell's cell; let CL be the electro-motive force of contact of C and L, and let CL be identical with—LC. Then :—

I. Daniell with pure satnrated copper sulphate and nearly pure saturated zinc suphate.

Observed EMF of cell measured directly.

$$CL_1 + L_1L_2 + L_2Z + ZC$$
$$= 0{\cdot}028 - 0{\cdot}033 + 0{\cdot}358 + 0{\cdot}750 = 1{\cdot}103$$

1·068 to 1·081, increasing slowly.

II. Daniell with distilled water and pure saturated copper sulphate.

$$CL_1 + L^{1}L_2 + L_2Z + ZC$$
$$= 0{\cdot}028 + 0{\cdot}071 + 0{\cdot}126 + 0{\cdot}750 = 0{\cdot}975$$

0·995.

III. Daniell with very dilute zinc sulphate and slightly impure saturated copper sulphate.

$$CL_1 + L_1L_2 + L_2Z + ZC$$
$$= 0 + 0{\cdot}063 + 0{\cdot}177 + 0{\cdot}750 = 0.990$$

1·010.

IV. Simple cell, nearly pure saturated zinc sulphate.

$$CL + LZ + ZC$$
$$= - 0{\cdot}113 + 0{\cdot}358 + 0{\cdot}750 = 0{\cdot}995$$

1·000.

V. Simple cell, distilled water.

$$CL + LZ + ZC$$
$$= 0{\cdot}074 + 0{\cdot}126 + 0{\cdot}750 = 0{\cdot}950$$

0·832 to 0·942 increasing slowly.

"In every case the sum of the separate contact electro-motive forces is so nearly equal to the observed maximum electro-motive force of the cell, that we have good reason for concluding that the electro-motive force of contact of any two substances measured inductively is constant for *exactly* the *same* specimens of the materials under *exactly the same condition* as regards temperature, the gaseous medium surrounding them, &c., and is quite independent of any other substances that may be in the circuit."

In the investigation made during 1877-78, and described in their third paper,* the authors have obtained the following results :—

* Phil. Trans. Roy. Soc., 1880, p. 15.

MEAN CONTACT DIFFERENCES OF POTENTIAL IN VOLTS; SOLIDS WITH SOLIDS IN AIR.†

	Carbon.	Copper.	Iron.	Lead.	Platinum.	Tin.	Zinc.	Amalgamated zinc.	Brass.	
Carbon	0	·370	·485*	·858	·113	·795*	1·096	1·208*	·414*	
Copper	— ·370	0	·146	·542	— ·238	·456	·750	·894	·087	
Iron	— ·485*	—·146	0	·401*	— ·369	·313*	·600*	·744*	—·064	The average tem-
Lead	— ·858	—·542	—·401*	0	— ·771	—·099	·210	·357*	—·472	perature at the
Platinum	— ·113*	·238	·369	·771	0	·690	·981	1·125*	·287	times these ex-
Tin	— ·795*	—·456	—·313*	·099	— ·690	0	·281	·463	—·372	periments were
Zinc	—1·096	—·750	—·600*	—·210	— ·981	—·281	0	·144	—·679	made was about
Amalgamated zinc	—1·208*	—·894	—·744	—·357*	—1·125*	—·463	—·144	0	—·822*	18° C.
Brass	— ·414	—·087	·064	·472	— ·287	·372	·679	·822*	0	

The numbers without an asterisk were obtained directly by experiment, those with an asterisk by calculation; using the well-known assumption that in a compound circuit of metals all at the same temperature there is no electro-motive force.

The numbers in a vertical column below the name of a substance are the differences of potential, in volts, between that substance and the substance in the same horizontal row as the number, the two substances being in contact. Thus lead is positive to copper, the electro-motive force of contact being 0·542 volt.

The metals were those of commerce, and therefore not chemically pure.

The authors point out that the contact difference between copper and zinc, which they find to be exactly ·750 volt, is a more convenient and reliable standard of electro-motive force, when it can be used, than even a Latimer Clark's cell.

† In the paper it is explained that in all probability if these quantetative experiments were made in other gases than air very different results would be obtained.

MEAN CONTACT DIFFERENCES OF POTENTIAL IN VOLTS; SOLIDS WITH LIQUIDS, AND LIQUIDS WITH LIQUIDS (IN AIR).

	Carbon.	Copper.	Iron.	Lead.	Platinum.	Tin.	Zinc.	Amalgamated zinc.	Brass.	Mercury.	Distilled water.	Alum solution, saturated at 15° C.	Copper sulphate solution, saturated at 15° C.	Zinc sulphate solution, saturated at 15°·3 C.	Zinc sulphate solution; specific gravity, 1·125 at 16°·9 C.	1 distilled water, 3 saturated solution zinc sulphate.	Strong nitric acid.
Mercury	·092	·308	·502	...	·156	...	...	...	...	...	...	...	...	...	...	...	...
Distilled water	·01 to ·17*	·269 to ·100	·148	·171	·285 to ·345	·177	−·105 to +·156	·100	·231	...	...	...	·043	·164	...	...	...
Solutions. Alum, saturated at 16°·5 C.	...	−·127	−·653	−·130	·246	−·225	−·536	...	−·014	...	...	...	...	...	...	...	...
Copper sulphate, saturated at 15° C.	...	·070	...	...	...	...	...	...	...	...	−·013	...	...	·095	...	·102	...
Copper sulphate solution; specific gravity, 1·087 at 16°·6 C.	...	·103	...	...	...	...	...	...	...	...	...	...	...	...	·090	...	...
Sea salt; specific gravity 1·18 at 20°·5 C.	...	−·475	−·605	−·267	−·856	−·334	−·565	...	−·435	...	...	...	...	...	...	...	...
Sal ammoniac, saturated at 15°·5 C.	...	−·396	−·652	−·189	·057	−·364	−·637	...	−·348	...	...	...	...	...	...	...	...
Zinc sulphate, saturated at 15°·3 C.	...	...	...	...	...	...	−·430	−·284	...	...	−·164	...	−·095	...	...	...	...
Zinc sulphate solution; specific gravity, 1·125 at 16°·9 C.	...	...	...	...	...	...	−·238	...	...	...	...	...	...	...	...	...	...
1 distilled water, mixed with 1 saturated solution zinc sulphate	...	...	...	...	...	...	...	...	...	...	...	...	−·093	...	...	...	...
1 distilled water, mixed with 3 saturated solution zinc sulphate	...	...	...	...	...	...	−·144	...	...	...	...	...	−·102	...	...	...	...

* Depending on the carbon.

MEAN CONTACT DIFFERENCES OF POTENTIAL IN VOLTS; SOLIDS WITH LIQUIDS, AND LIQUIDS WITH LIQUIDS (IN AIR)—*continued*

		Carbon.	Copper.	Iron.	Lead.	Platinum.	Tin.	Zinc.	Amalgamated zinc.	Brass.	Mercury.	Distilled water.	Alum solution, saturated at 15° C.	Copper sulphate solution, saturated at 15° C.	Zinc sulphate solution, saturated at 15° 3 C.	Zinc sulphate solution; specific gravity, 1·125 at 16° 9 C.	1 distilled water, 3 saturated solution zinc sulphate.	Strong nitric acid.
Dilute sulphuric acid.	Distilled water, with a slight trace of sulphuric acid	...	...	...	...	...	...	−·241	...	...	...	...	...	...	...	...	...	·078
	Distilled water, with about one-fifth per cent. of sulphuric acid	...	...	...	...	...	...	−·289	...	...	...	...	...	...	...	...	...	...
	Distilled water, with about one-third per cent. of sulphuric acid	...	...	...	...	...	...	−·312	...	...	...	...	...	...	...	...	...	...
	By weight—20 distilled water, 1 strong sulphuric acid	...	...	...	...	...	...	−·344	...	...	...	...	...	...	...	...	...	...
	By volume—10 distilled water, 1 strong sulphuric acid	About −·035	...	...	...	...	...	...	−·358	...	...	...	...	...	...	...	...	...
	By weight—5 distilled water, 1 strong sulphuric acid	...	...	...	...	...	...	...	−·429	...	...	...	...	...	...	...	...	...
	1 distilled water, 5 strong sulphuric acid	·01 to ·3	...	...	−·120	...	−·256	...	...	·016	...	...	...	...	...	...	...	...
Concentrated.	Sulphuric acid	·55 to ·85*	1·113	...	·720 to 1·252	1·600 to 1·300	...	...	·848	...	...	1·298	1·456	1·269	1·699	...	...	...
	Nitric acid	...	...	...	...	·672	...	...	...	...	...	...	...	...	...	...	...	...
	Mercurous sulphate paste	...	...	...	...	...	...	...	...	...	·475	...	...	...	...	...	...	...

* Depending on the carbon.

The average temperature at the time these experiments were made was about 16° C. All the liquids and salts employed were chemically pure; the solids, however, were only commercially pure. The numbers in a vertical column below the name of a substance are the differences of potential, in volts, between that substance and the substance in the same horizontal row as the number, the two substances being in contact. Thus:—Lead is positive to distilled water, and the contact difference of potentials is 0·171 volts.

The authors point out that in all these experiments two air-contacts enter, and that up to the present time no direct experiment has enabled the difference of potential at *each* of these to be measured. They therefore show the importance of repeating their *quantitative* experiments on the electro-motive force of contact in other gases besides air, and especially in a very perfect vacuum; and they mention that, although they made the working drawings of the apparatus necessary for this extended investigation at the beginning of 1877, it was not until now that they have been enabled to commence it.

They further add:—"If the gas measurements such as we have indicated be extended to a good Crookes' vacuum, we may then possibly approximate to the real value of A B, the contact difference of potentials of A with B, the value in fact that we should obtain by a measurement of the Peltier effect.

RESULTS.

"The results which have been already obtained in this present investigation group themselves under three heads:—

"1st. The contact difference of potentials of metals and liquids at the same temperature.

"2nd. The contact difference of potentials of metals and liquids when one of the substances is at a different temperature from the other in contact with it; for example, mercury at 20° C. in contact with mercury at 40° C.

"3rd. The contact difference of potentials of carbon and of platinum with water, and with weak and strong sulphuric acid.

"But those contained under head No. 1. are alone contained in the present paper." *

* The authors hope to have the honour of submitting the remainder of their completed experiments on a subsequent occasion to the Royal Society.

CHAPTER XLIV.

DIMENSIONS OF UNITS.*

As a familiar illustration of dimensions let us consider a linear, square, and cubic yard.

A linear yard is said to be of one dimension in length.

A square yard of two dimensions because it is a $(\text{yard})^2$.

A cubic yard of three dimensions because it is a $(\text{yard})^3$.

Thus, any length is expressed by a number multiplied by the unit of length, and this unit of length is said to be of one dimension.

The units of area and volume are said respectively to be of two and three dimensions. This much is obvious.

DERIVED UNITS—VELOCITY.

Now let us consider derived units: of these, velocity is the simplest.

The velocity with which anything moves, when moving uniformly, is the distance traversed divided by the time occupied by the journey. Thus, a train which travelled 140 miles in four hours would have a velocity of $\frac{140}{4} = 35$, when the units of length and time were the mile and the hour. If, however, the units were the yard and hour, the same velocity would be expressed by the number (35×1760), whereas, if the units were the mile and minute, the same velocity would be expressed by the number $\frac{35}{60}$. Thus the numerical number of the same velocity is greater when the unit of length is small, and, further, it varies inversely as the unit of length.

* On this subject the student is requested to read "Units and Physical Constants," by Dr. Everett (Macmillan), from which much of this chapter is taken.

But the magnitude of the unit of velocity is inversely as the number of units which make a given velocity. Hence the unit of velocity varies directly as the unit of length.

Again, with regard to the unit of time.

The numerical value of a given velocity is less when the unit of time is less, and it varies directly as the unit of time.

But the magnitude of the unit of velocity is inversely as the number of such units which express a given velocity.

Hence the unit of velocity varies inversely as the unit of time. That is, the unit of velocity varies directly as the unit of length and inversely as the unit of time.

This is expressed by saying that velocity is of one dimension in length and minus one (—1) in time.*

Kepler's law of planetary motion discusses the area swept out in a given time by the straight line (called the radius vector) joining the sun and a moving planet. The area swept out in a unit of time may be called the area-velocity of the radius vector

By exactly similar reasoning to that on the last page we shall see that the unit of area velocity is directly as the unit of area and inversely as the unit of time.

Hence its dimensions are one in area and minus one in time.

But the unit of area is the unit of length squared, that is, area is of two dimensions in length.

Hence the unit of area-velocity is of two dimensions in length and minus one in time.

Maxwell's Notation.

It is customary to write units in square brackets.

Thus, a length L may be written

$$L\,[L]$$

where L is a number and [L] the unit of length.

On this plan, then, we may write

$$[\text{Length}] = [L]$$
$$[\text{Area}] = [L^2]$$
$$[\text{Volume}] = [L^3]$$
$$[\text{Velocity}] = \left[L\,T^{-1}\right] \text{ sometimes written } \left[\frac{L}{T}\right]$$
$$[\text{Area Velocity}] = \left[L^2\,T^{-1}\right] \text{ or } \left[\frac{L^2}{T}\right]$$

* See Todhunter's "Algebra;" Theory of Indices, p. 147. Art. 258.

Unit of Force.

When a body is in uniform motion, Newton's second law* tells us that force is required to change the motion, and that the change of motion is proportional to the impressed force.

Change of motion means change of velocity, and this includes change of direction; for to change the direction of motion of a body a velocity must be given to it in a direction inclined to its first direction.

Suppose a body to be moving northward with a given velocity, then, to cause it to move in a north-easterly direction with the same velocity, we must add a velocity whose direction is between north-east and south.

Thus we have a natural method of measuring forces when we assert that a unit force is that which, acting on a body of unit mass, can produce a change of velocity equal to unity in a unit of time.

For instance, the velocity of a falling body continually increases because the force of gravitation is accelerating it. The number of centims. per second by which the velocity increases is the measure of the force with which gravitation acts on each gramme of the body.

Now, if the unit of velocity is great, a greater force will be equal to unity, as it will have to make a greater change of velocity in a given time; therefore the unit of force varies directly as the unit of velocity.

If the unit of time is great, the unit of force will be small, as a less force will be required to produce a given change in a long time than in a short one. Hence the unit of force is inversely as the unit of time, and directly as the unit of velocity.

Again, if the unit of mass is great, the unit of force will be great, for more force is required to produce a given change of velocity in a given time on a great mass than on a small one; hence the unit of force varies directly as the unit of mass.

We have then—unit of force varies directly as units of velocity and mass, and inversely as unit of time; or if we write

$$[F] \qquad [V] \qquad [M]$$

for units respectively of force, velocity, and mass, we have

* Lex II.—Mutationem motus proportionalem esse vi motrici impressæ, et fieri secundum lineam rectam qua vis illa imprimitur.

$$[F] = \left[M\,V\,T^{-1}\right] \text{ or } \left[\frac{M\,V}{T}\right].$$

But the unit of velocity also contains the unit of time once inversely, for

$$[V] = L\,T^{-1}.$$

Therefore, on substituting its value for [V], we shall have

$$[F] = \left[M\,L\,T^{-1}\,T^{-1}\right] = \left[M\,L\,T^{-2}\right]$$

or

$$\left[\frac{M\,L}{T^2}\right].$$

RATIO OF UNITS.

It is obvious that the dimensions of different units bear certain ratios to each other; sometimes these ratios have an obvious physical meaning, sometimes not. For instance, the ratio of volume to area is

$$\left[\frac{L^3}{L^2}\right] = [L],$$

the meaning of which is clear enough.

The ratio of force to velocity is

$$\left(\frac{\frac{M\,L}{T^2}}{\frac{L}{T}}\right) = \left[\frac{M}{T}\right]$$

which has no obvious meaning.

THE TWO SETS OF ELECTRIC UNITS.

Now we know that there are two systems of measuring electric effects, the electro-static and the electro-magnetic. If we in each case set to work to derive the units by which the effects are to be measured from the fundamental units of time, length, and mass, we shall arrive at two different systems.

We propose to do this, and, having compared the two systems, see what physical meaning we can give to their ratio.

ELECTRO-STATIC UNIT OF QUANTITY.

In the electro-static system the unit quantity of electricity is that quantity which, if collected at a point, will repel another equal quantity at a unit distance with a unit of force. In the C.G.S. system a unit of electricity is that quantity which would repel

an equal quantity at a distance of one centim. with a force of one dyne.*

The force between two quantities of electricity, each equal to q at a distance l from one another, would be

$$\frac{q^2}{l^2}.$$

The unit of electrical force may then be written

$$\left[\frac{Q^2}{L^2}\right].$$

But in order that this may agree with the mechanical units where unit of force is

$$\left[\frac{M\,L}{T^2}\right]$$

we must have

$$\left[\frac{Q^2}{L^2}\right] = \left[\frac{M\,L}{T^2}\right]$$

or

$$[Q^2] = \left[\frac{M\,L^3}{T^2}\right]$$

which gives us for the dimensions of unit electrical quantity in the electro-static system,

$$[Q] = \left[\sqrt{\frac{M\,L^3}{T^2}}\right] = \left[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\right].$$

Electro-static Unit of Current.

The numerical value of a current in electro-static units is on the C.G.S. system defined to be the quantity of electricity which passes in a unit of time. Hence the dimensions of a current are, in electro-static measure,

$$\left[\frac{Q}{T}\right] = \left[M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}\right].$$

Electro-magnetic Unit of Current.

On the electro-magnetic system, a current flowing along a circular arc is measured by the "intensity of magnetic field" which it produces at the centre of the arc.

* A dyne is that force which, acting on a unit of mass, would change its velocity 1 centim. per second in one second. Gravity = about 981 dynes per gramme; weight of a gramme = 981 dynes; force of gravity on a gramme = 981 dynes.

Intensity of Magnetic Field.

The intensity of magnetic field is equal to C, the strength of the current, multiplied by length of arc, divided by square of radius.

Therefore, if [I] be the unit of intensity of magnetic field, we shall have

$$[\mathrm{I}] = \left[\frac{\mathrm{C\,L}}{\mathrm{L}^2}\right]$$

or

$$[\mathrm{C}] = [\mathrm{I\,L}].$$

The unit magnetic pole is that which repels a similar unit pole at unit distance with a unit of force. In the C.G.S. system it is one which repels a similar pole distant 1 centim. with a force of 1 dyne. The force between two poles of strengths P_1 and P_2 is equal to their product divided by the square of their distance from one another.

Hence we have for the equation of units

$$\left[\frac{\mathrm{P}^2}{\mathrm{L}^2}\right] = \left[\frac{\mathrm{M\,L}}{\mathrm{T}^2}\right]$$

or

$$[\mathrm{P}] = \left[\mathrm{M}^{\frac{1}{2}}\,\mathrm{L}^{\frac{3}{2}}\,\mathrm{T}^{-1}\right].$$

The intensity of a magnetic field is the force which a unit pole will experience when placed within it. Denoting this intensity by I, the force on any pole will be I P.

Hence

$$[\mathrm{I\,P}] = \left[\frac{\mathrm{M\,L}}{\mathrm{T}^2}\right].$$

Dividing both sides of the equation by [P] we have

$$[\mathrm{I}] = \left[\frac{\frac{\mathrm{M\,L}}{\mathrm{T}^2}}{\frac{\mathrm{M}^{\frac{1}{2}}\,\mathrm{L}^{\frac{3}{2}}}{\mathrm{T}}}\right] = \left[\frac{\frac{\mathrm{M}^{\frac{1}{2}}}{\mathrm{T}}}{\mathrm{L}^{\frac{1}{2}}}\right] = \left[\mathrm{M}^{\frac{1}{2}}\,\mathrm{T}^{-1}\,\mathrm{L}^{-\frac{1}{2}}\right] = \left[\mathrm{M}^{\frac{1}{2}}\,\mathrm{L}^{-\frac{1}{2}}\,\mathrm{T}^{-1}\right].$$

Current.

Returning to our current equation

$$[\mathrm{C}] = [\mathrm{I\,L}]$$

we have

$$[\mathrm{C}] = \left[\mathrm{M}^{\frac{1}{2}}\,\mathrm{L}\,\mathrm{L}^{-\frac{1}{2}}\,\mathrm{T}^{-1}\right] = \left[\mathrm{M}^{\frac{1}{2}}\,\mathrm{L}^{\frac{1}{2}}\,\mathrm{T}^{-1}\right].$$

Electro-magnetic Unit of Quantity.

Now in the electro-magnetic system the quantity of electricity conveyed by a current is equal to the strength of the current multiplied by the time which it lasts.

The unit of electrical quantity on the electro-magnetic system then is

$$[Q] = [C\,T] = \left[M^{\frac{1}{2}}\,L^{\frac{1}{2}}\,T^{-1}\,T\right] = \left[M^{\frac{1}{2}}\,L^{\frac{1}{2}}\right].$$

Ratio of Two Units of Quantity.

Postponing for a while the discussion of the dimensions of other electrical quantities, we will consider the ratio of the two units of electrical quantity.

We have

Dimensions of electrical quantity

On the electro-static system

$$\left[M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-1}\right].$$

On the electro-magnetic system

$$\left[M^{\frac{1}{2}}\,L^{\frac{1}{2}}\right].$$

Ratio of

$$\frac{\text{Dim. in E. S.}}{\text{Dim. in E. M.}} = \left[L\,T^{-1}\right] \text{ or } \left[\frac{L}{T}\right].$$

Thus the ratio of the dimensions of the two units of quantity is a *velocity*.

It will be shown in the next chapter,* that this velocity has a real existence, and the physical meaning of it will there be explained.

We will now briefly give the dimensions of other electrical quantities.

Electro-static Unit of Potential.

The dimensions of work are force multiplied by distance through which it acts

Hence

$$[W] = \left[M\,L\,T^{-2}\,L\right] = \left[M\,L^{2}\,T^{-2}\right].$$

The work done in raising the potential of a quantity of electricity Q through a difference of potential V is

$$Q\,V.$$

---

* Vol. ii. pp. 192, 200.

Hence we have

$$[V] = \frac{[W]}{[Q]} = \left(\frac{M\,L^2\,T^{-2}}{M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T}\right) = \left[M^{\frac{1}{2}}\,L^{\frac{1}{2}}\,T^{-1}\right].$$

ELECTRO-STATIC UNIT OF CAPACITY.

The capacity of a conductor is the quotient of the quantity of electricity with which it is charged by the potential which this charge produces in it.

Hence we have

$$[\text{Capacity}] = \left[\frac{Q}{V}\right] = \left(\frac{M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-1}}{M^{\frac{1}{2}}\,L^{\frac{1}{2}}\,T}\right) = [L].*$$

ELECTRO-STATIC UNIT OF RESISTANCE.

The resistance of a conductor is equal to the time required for the passage of unit quantity of electricity through it when unit difference of potential is maintained at its ends.

It therefore varies directly as the time, also directly as the difference of potential; for if we increase the difference of potential, we must increase the resistance if we wish to keep the time the same.

It varies inversely as the quantity, for if a greater quantity is to pass in a given time, the resistance must be less.

Hence

$$[R] = \left[\frac{T\,.\,V}{Q}\right] = \left(\frac{T\,.\,M^{\frac{1}{2}}\,L^{\frac{1}{2}}\,T^{-1}}{M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-1}}\right) = \left[L^{-1}\,T\right],$$

or

$$\left[\frac{T}{L}\right]$$

viz. reciprocal of a velocity.

ELECTRO-MAGNETIC UNITS OF ELECTRO-MOTIVE FORCE AND POTENTIAL.

The work done in urging a quantity q of electricity through a circuit by an electro-motive force E is E q. And the work done in urging a quantity q through a conductor by means of a difference of potential E is also E q. Hence the dimensions of electro-motive force and also the dimensions of potential are

$$[E] = \left(\frac{M\,L^2\,T^{-2}}{L^{\frac{1}{2}}\,M^{\frac{1}{2}}}\right) = \left[M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-2}\right].$$

---

* Compare vol. i. p. 67.

Electro-magnetic Unit of Capacity.

Capacity is the quotient of quantity of electricity by potential. Its dimensions therefore are

$$\left[\frac{M^{\frac{1}{2}}L^{\frac{1}{2}}}{M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}}\right] = [L^{-1}T^{2}]$$

Electro-magnetic Unit of Resistance.

Resistance equals

$$\frac{E}{C}$$

therefore

$$[R] = \left[\frac{M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}}{M^{\frac{1}{2}}L^{\frac{1}{2}}T}\right] = [L\,T^{-1}].$$

That is, as we saw in discussing the B A unit in vol. i., page 286, electro-magnetic resistance is a velocity.

Summary.

The following table summarizes the results we have just obtained :—

	Dimens. in E. S.	Dimens. in E. M.	Ratio $\frac{\text{Dim. in E. S.}}{\text{Dim. in E. M.}}$
Quantity . . .	$M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}$	$M^{\frac{1}{2}}L^{\frac{1}{2}}$	$L\,T^{-1}$
Current . . .	$M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}$	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$	$L\,T^{-1}$
Capacity . . .	L	$L^{-1}T^{2}$	$L^{2}T^{-2}$
Potential and Electromotive Force .	$M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$	$M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-2}$	$L^{-1}T$
Resistance . .	$L^{-1}T$	$L\,T^{-1}$	$L^{-2}T^{2}$

Ratio of the Two Sets of Electric Units.

The following explanation of the ratios between the two sets of electric units is due to Professor Everett :*—

* "Units and Physical Constants," p. 132.

We know that in the C.G.S. system—

The unit of length = 1 centim.
The unit of mass = 1 gramme.
The unit of time = 1 second.

Let us consider some other general system in which

The unit of length = L centims.
The unit of mass = M grammes.
The unit of time = T seconds.

Then the new electro-static unit of quantity will equal

$$M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-1} \text{ C.G.S. electro-static units of quantity.}$$

And the new electro-magnetic unit of quantity will equal

$$M^{\frac{1}{2}}\,L^{\frac{1}{2}} \text{ C.G.S. electro-magnetic units of quantity.}$$

Now it is possible so to select L and T that the new electro-static unit of quantity is equal to the new electro-magnetic unit.

In order to determine what the values of L and T must be to satisfy this condition, we have, substituting the values of the new units in C.G.S. units, the equation

$$\left\{ \begin{matrix} M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-1} \text{ C.G.S. electro-static} \\ \text{units of quantity.} \end{matrix} \right\} = \left\{ \begin{matrix} M^{\frac{1}{2}}\,L^{\frac{1}{2}} \text{ C.G.S. electro-magnetic} \\ \text{units of quantity.} \end{matrix} \right\}$$

Dividing out by $M^{\frac{1}{2}}\,L^{\frac{1}{2}}$ we have

$$L\,T^{-1} \text{ C.G.S. electro-static units of quantity} = 1 \text{ C.G.S. electro-magnetic unit of quantity.}$$

or the ratio of the C.G.S. electro-magnetic unit of quantity to the C.G.S. electro-static unit is $\frac{L}{T}$.

We see that $\frac{L}{T}$ is clearly the value in centims. per second of that velocity which would be denoted by unity in our "new" system. This is a *definite concrete velocity*, and its numerical value will always be equal to the ratio of the electro-magnetic to the electro-static unit of quantity, *whatever units of length, mass, and time are employed.*

It will be observed that *the ratio of the two units of quantity is the inverse ratio of their dimensions*, and the same can be proved in the same way of the other four electrical elements.

The last column of the table on page 188 shows that M does not enter into any of the ratios, and that L and T always enter with equal and opposite indices, that is that *all the ratios depend only on the velocity* $\frac{L}{T}$.

Thus if the concrete velocity $\frac{L}{T}$ be a velocity of v centims. per second, there will be the following relations between the C.G.S. units.

1	electro-magnetic unit of	quantity	$=$	v	electro-static units.
1	„ „	current	$=$	v	„ „
1	„ „	capacity	$=$	v^2	„ „
v	electro-magnetic units of	potential	$=$	1	electro-static unit.
v^2	„ „	resistance	$=$	1	„ „

CHAPTER XLV.

EXPERIMENTAL COMPARISON OF ELECTRO-STATIC AND ELECTRO-MAGNETIC UNITS.

We have shown that electro-static and electro-magnetic phenomena are measured by two different sets of units, or rather that two distinct systems of units have grown up—one based on an electro-static, and the other on an electro-magnetic unit of quantity; but either may be used in the measurements of any phenomena. We have also seen that the relation of the electro-magnetic unit of quantity to the electro-static is the relation of a length to a time—in other words, it is a velocity.

By a purely mathematical process of reasoning,* which it is impossible to put into a non-mathematical form, Professor Maxwell has shown that this velocity is the velocity with which electro-magnetic disturbance is propagated through space—that is, if a sudden difference of magnetic potential be caused at any point, the disturbance due to it will be felt at any other point after an interval which, on being compared with the distance between the points, shows the disturbance to have been propagated with this velocity. This velocity has never been measured directly, as, even at a distance of 100 yards, the disturbance caused by any change of potential which we can produce would be quite insensible, and the velocity, which, as we shall presently show, is about the same as that of light, is so great that the time required for the disturbance to pass over a short interval is extremely small. It is, however, possible that, if necessary, some method of direct measurement might be devised; but the indirect method of comparison of units is as certainly a measure of the velocity of the disturbance, and is capable of far greater accuracy than is ever likely to be obtained by the direct method.

* Clerk Maxwell, "Electricity," Articles 783—786, vol. ii., pp. 384—387.

The Ratio is a Velocity.

The following physical proof that the ratio of the units is a velocity is given by Professor Maxwell :—

Let there be two parallel currents—the attraction experienced by a length a of one of them is—

$$F = 2\,CC'\frac{a}{b},$$

where C, C′ are the numerical values of the currents in electro-magnetic measure, and b is the distance between them. If we so choose the length a that we are considering that $b = 2\,a$ we shall have—

$$F = CC'.$$

Let us put n for the number of electro-static units in one electro-magnetic unit, we have to show that n is a velocity.

The quantity of electricity transmitted by a current C in a time t is we know equal to $C\,t$ in electro-magnetic measure, and therefore to nCt in electro-static measure, because n is the number of electro-static units in one electro-magnetic unit.

We know that the repulsion F′ between two statically-charged bodies at a distance apart r and having charges q and q' is

$$F' = \frac{q\,q'}{r^2}.\text{*}$$

Let two small conductors be charged with quantities $q\ q'$ equal to the quantities transmitted in time t by the currents $C\,C'$ respectively, then their charges in electro-static measure will be—

$$q = n\,C\,t, \quad q' = n\,C'\,t,$$

and the electro-static repulsion F′ between them will be—

$$F' = \frac{n\,C\,t,\,n\,C'\,t}{r^2} = \frac{C\,C'\,n^2\,t^2}{r^2}.$$

Let the distance r be varied until this repulsion equals the electro-magnetic attraction F, we have $F = F'$ or

$$C\,C' = \frac{C\,C'\,n^2\,t^2}{r^2}$$

Dividing out by $C\,C'$ we have

$$1 = \frac{n\ \ t^2}{r^2}$$

or

$$n^2\,t^2 = r^2,$$

* Vol. i. p. 19.

that is

$$n\,t = r$$

or

$$n = \frac{r}{t}$$

—that is n, the number of electro-static units in one electro-magnetic unit, equals a length (r) divided by a time (t)—that is, *equals a velocity*.

The absolute magnitude of this velocity is the same whatever units we adopt.

Theory of the Experiments.

We now come to the experimental methods of determining the ratio of the units.

The general principle of them all is to measure the same thing both electro-statically and electro-magnetically. Different numbers are obtained in the two cases. But when the same thing is measured by two different sets of units, the ratio of the numbers obtained in the two cases is the inverse ratio of the units used.

For instance, suppose we did not know the ratio of a foot to a yard, but were able to measure any distance both in feet and in yards.

To determine the ratio of the units we should take an arbitrary distance and measure it—first using the yard for the unit and then the foot.

Suppose we found that the number obtained in the first case was 60, and in the second 180, we then have, ratio of number obtained with yard unit to number obtained with foot unit equals 60 to 180, or 1 to 3. Therefore the ratio of the yard to the foot is the inverse of this ratio, or 3 to 1.

Similarly, in the electrical case, we measure the same quantity of electricity first in electro-static units and then in electro-magnetic units.

The ratio of the numbers obtained is the inverse ratio of the electro-static to the electro-magnetic unit of quantity.

Experimental Methods of Determining the Ratio between Electro-static and Electro-magnetic Units.

The first numerical determination of this velocity was made by Weber and Kohlrausch.*

* Pogg. xcix., August 10, 1856, and Maxwell, 771, vol. ii. p. 370.

The following account of these experiments is given by Professor Maxwell:—

"Their method was founded on the measurement of the same quantity of electricity—first in electro-static and then in electro-magnetic measure.

"The quantity of electricity measured was the charge of a Leyden jar. It was measured in electro-static measure by the product of the capacity of the jar into the difference of potential of its coatings.

"The capacity of a sphere is expressed in electro-static measure by its radius. Thus the capacity of the jar may be found and expressed as a certain length.*

"The difference of the potentials of the coatings of the jar was measured by connecting the coatings with the electrodes of an electrometer whose constants had been carefully determined, so that the difference of the potentials was known in electro-static measure. By multiplying this by the capacity of the jar the charge of the jar was expressed in electro-static measure."

To determine the value of the charge in electro-magnetic measure the jar was discharged through the coil of a galvanometer. The total current could then be calculated from the limit of the first swing of the needle.

This comparison gave for the ratio of the units, which is commonly called v,

$$v = 3{\cdot}1074 \times 10^{10} \text{ centims. per second.}$$

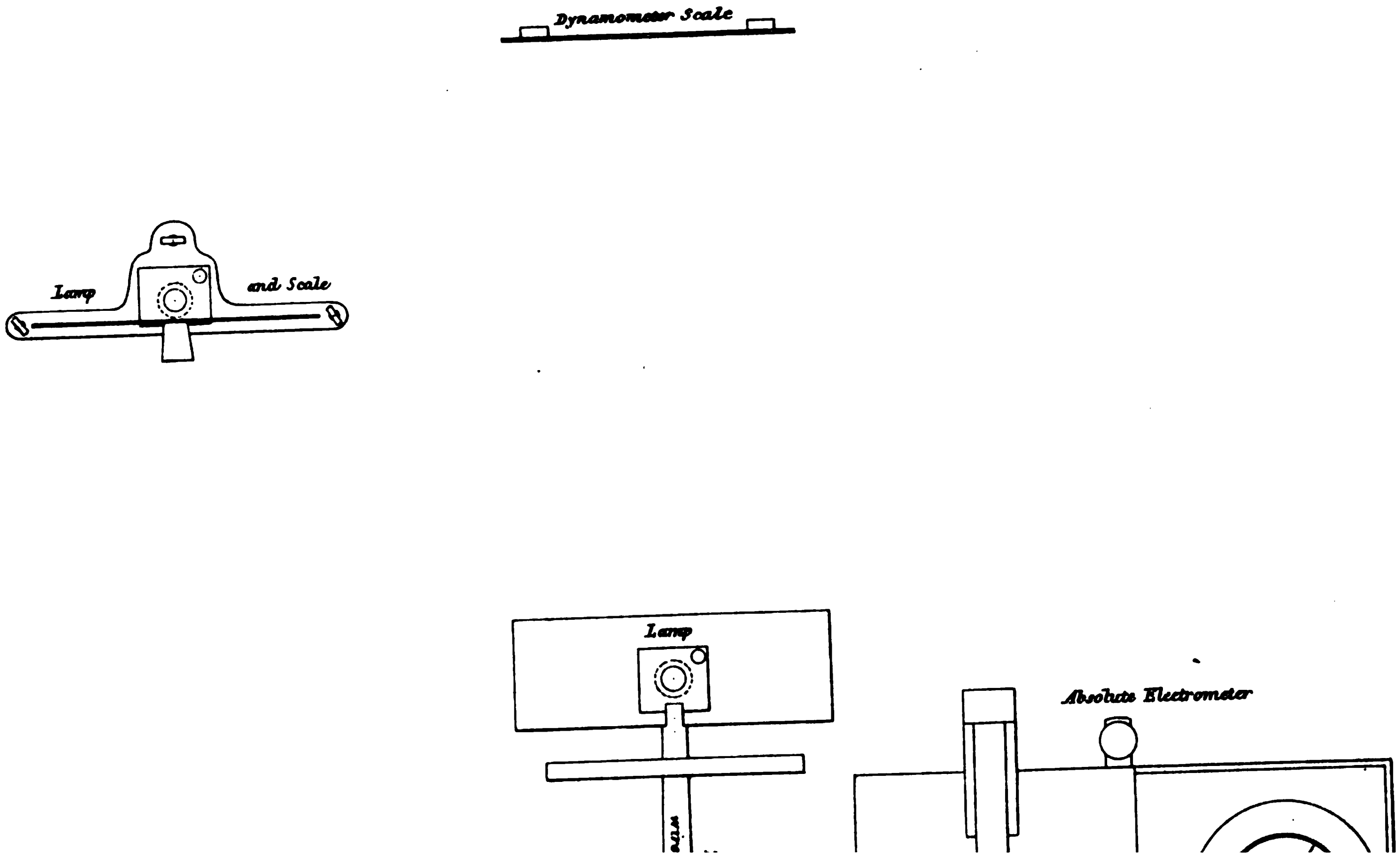
Professor Maxwell has pointed out that the phenomenon known as "Electric Absorption," which, at the date of these experiments, was not well understood, makes it almost impossible to estimate correctly the charge of a jar unless the experiments are performed instantaneously. He shows that the effect of neglecting absorption would be to make the value of v deduced by this method too high.

Sir Wm. Thomson's Comparison.—Plate XLIX.

Sir Wm. Thomson has determined v, the ratio of the units, by measuring the same electro-motive force in both sets of units.

Electro-motive force is measured in electro-static units directly by means of an electrometer.

* See vol. ii. p. 187.



Dynamometer Scale
Lamp
and Scale
Lamp
Absolute Electrometer
wire

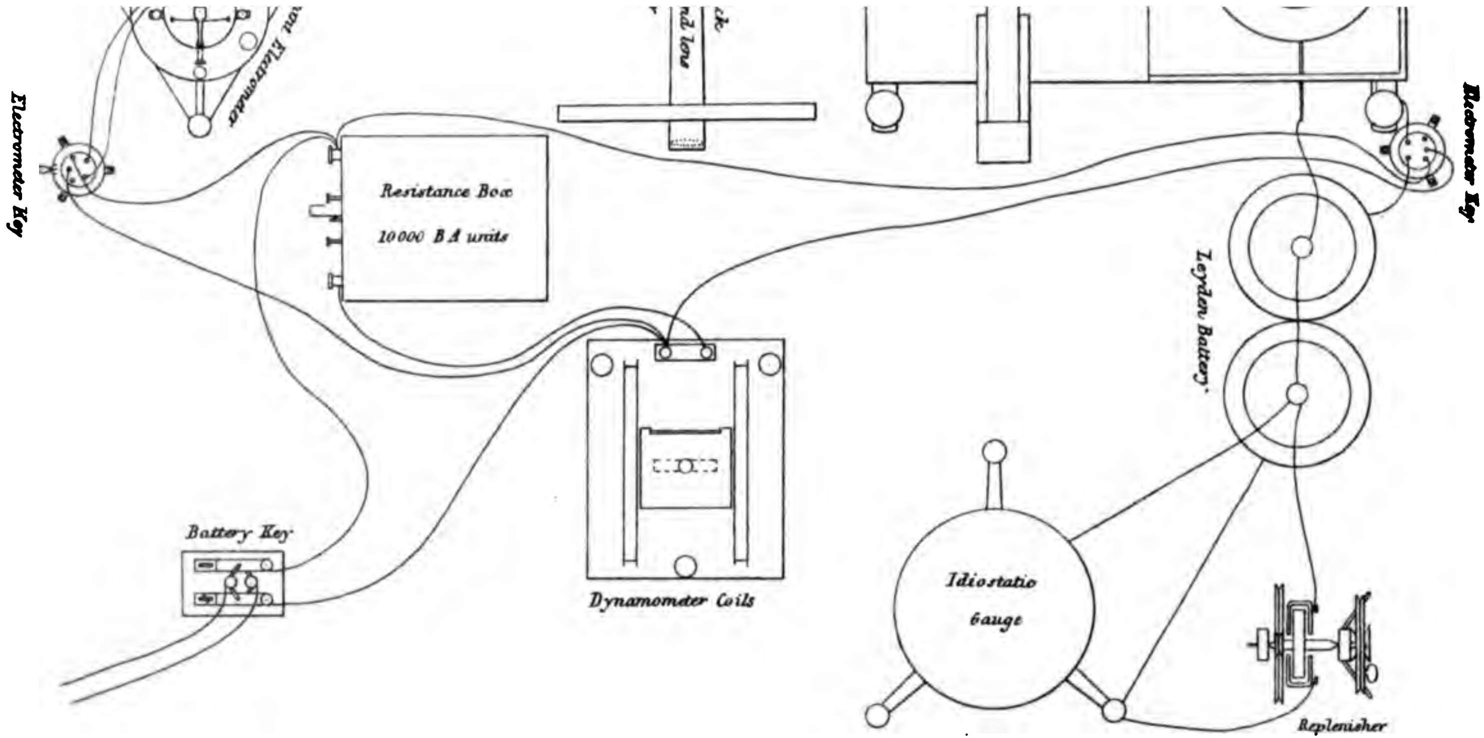


Plate XLIX. *Ratio of Electric Units.—Thomson.*

By Ohm's law we know that

$$E = Cr,$$

and C and r can be measured in electro-magnetic measure.

For suppose that E equals A electro-static units, and that the current C which it can produce through a resistance r is such that $Cr = B$ electro-magnetic units; then, if we measure A and B, we shall have

$$\frac{B}{A} = v, \text{ the ratio required,}$$

for 1 electro-static unit of potential equals v electro-magnetic units.

In Sir Wm. Thomson's experiments the difference of potential was measured (statically) by electrometers, and the current, through a known resistance, by the deflection of the suspended coil of an electro-dynamometer.*

Plate XLIX. shows the arrangements.†

But little explanation is required. The dynamometer has been already described, as have the various electrometers. The chief circuit is that of the resistance coils, battery, and dynamometer, with branches to the absolute electrometer. The gauge, Leyden battery, and replenisher, are the usual appendages of the electrometer.

The quadrant electrometer was used solely as a convenient method of determining the resistance of the dynamometer coils while the experiments were going on; and thus eliminating changes of resistance due to changes of temperature produced by the current. It was used by connecting its terminals alternately at each side of the resistance coil, whose resistance was known, and of the dynamometer coils.

We can deduce, from vol. i., p. 306, that in any circuit the resistance between any two points is simply proportional to the difference of potential at those points. Hence the resistance of the dynamometer is to that of the coils as the difference of the potentials on each side of it to the corresponding difference at each side of the resistance coils.

The battery used was sixty sawdust Daniell's in series.

The value of the ratio given by Sir William Thomson in 1869, as determined by this method, is as follows:—"Eleven sets of

* Vol. ii. p. 3.

† "Reports on Electrical Standards," p. 186.

experiments made at various dates from March 10th to May 8th, 1868, have indicated values for the ratio which is called v, of which the greatest was $2 \cdot 92 \times 10^{10}$, the smallest $2 \cdot 754 \times 10^{10}$ and the mean $2 \cdot 825 \times 10^{10}$ centimetres per second."

Sir William Thomson, at the end of his paper, expressed his intention of carrying his experiments to a much greater degree of accuracy.

McKichan's Experiments.

This intention was carried out by Mr. Dugald McKichan, who, working in Sir William Thomson's laboratory, made, in 1870-72, a series of measurements of which the results were communicated to the Royal Society on April 15, 1873, and will be found in the Philosophical Transactions for that year.*

The experiments only differed in detail from those already described.

The final series of values of v determined on February 21, 1872, were as follows :—

v in centims. per second.
$2 \cdot 934 \times 10^{10}$
$2 \cdot 935$ "
$2 \cdot 931$ "
$2 \cdot 923$ "
$2 \cdot 935$ "
$2 \cdot 935$ "

The mean value adopted by Mr. McKichan is

$$2 \cdot 93 \times 10^{10}$$

Clerk Maxwell's Direct Comparison.

Professor Clerk Maxwell has compared the two units of electro-motive force by balancing the attraction between two oppositely-charged discs against the repulsion between two currents carried in two flat spirals of known resistance, the ratio between the electro-motive forces used in charging the discs and in sending the currents through the spirals being known, and the electro-motive forces being measured electro-statically.

Plate L. shows the arrangements.

* Phil. Trans., 1873, p. 409. The mathematical theory of the experiments is very fully given in this paper.

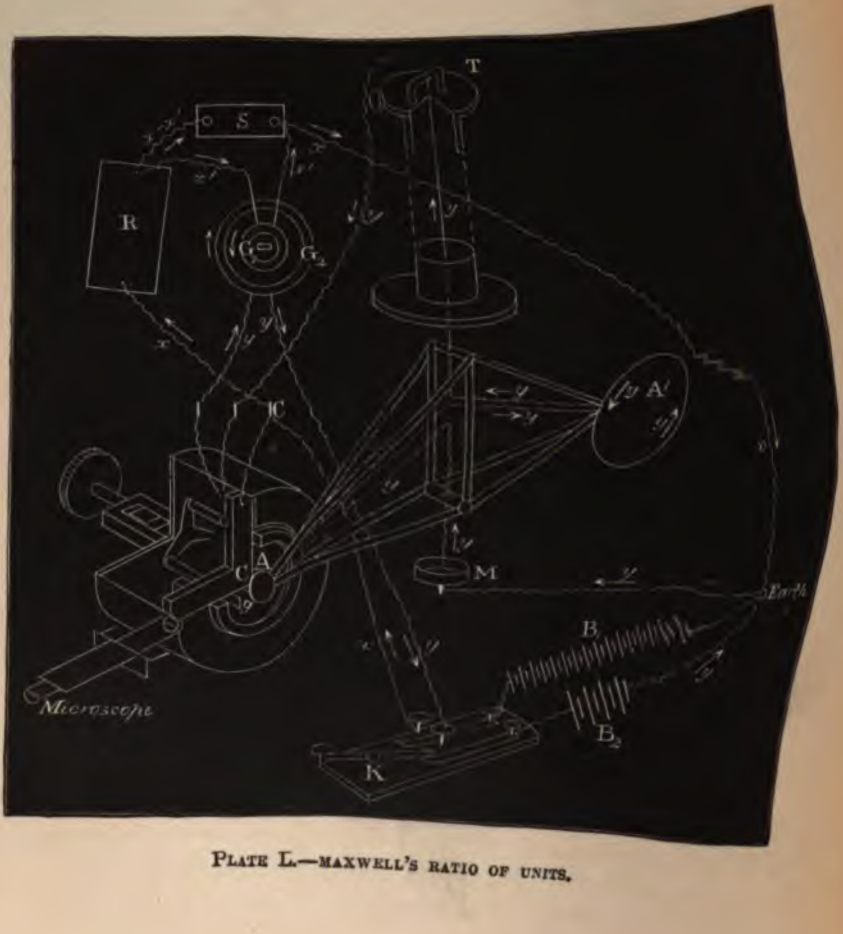


PLATE L.—MAXWELL'S RATIO OF UNITS.

EXPLANATION OF PLATE L.

A	Suspended disc and coil.	C	Electrode of fixed disc.
A	Counterpoise " "	x	Curren through R.
C	Fixed " "	x'	" " G_1.
B_1	Great Battery.	$x-x'$	" " S.
B_2	Small Battery.	y	" " the 3 coils and G_2.
G_1	Primary coil of Galvanometer.		
G_2	Secondary " "	M	Mercury cup.
R	Great Resistance.	T	Torsion head and tangent screw.
S	Shunt.		
K	Double key.	g	Graduated glass scale.

G and S 10 ft. from Electric balance.

One disc and spiral were fixed, and the others were attached together to the same end of the arm of a torsion balance.

To the other end of the arm was fixed an exactly similar coil, through which the same current travelled in the opposite direction to that in which it passed through the first suspended coil. The effect of the extra coil was to neutralize the action of terrestrial magnetism on the arm of the torsion balance. The small suspended disc was surrounded by a guard-ring similar to that used by Sir William Thomson in his absolute electrometers. This insured that the electrical action on the small disc should be equal to that due to a uniform distribution over its front surface. The suspended disc was four inches diameter, and was kept at the same potential as the case of the instrument.

The fixed disc was 6 inches diameter, and could be moved nearer to, or farther from, the guard-ring by means of a micrometer screw. It was insulated and maintained at a high potential during the experiments. When the suspended disc was in its position of equilibrium, its plane corresponded with that of the guard-ring.

The coils were fixed at the backs of the fixed and suspended discs respectively; special means were taken to insulate the one placed in contact with the disc which was intended to be charged to a high potential.

The electro-static charge was given by connecting the discs to the terminals of a great battery of 2600 cells charged with corrosive sublimate. The difference of potential at its ends was measured by observing, by means of a galvanometer, the current which it could send through a known very large resistance. The currents through the coils were produced by a smaller battery, and measured in the ordinary way by a galvanometer.

Thus we have two electro-motive forces whose ratio is known—one acting electro-statically, the other electro-magnetically. Their strength being adjusted until the attraction of the discs equals the repulsion of the coils—that is, until the suspended arm of the torsion balance is in equilibrium; and proper corrections having been made for the different distances apart of the discs and the coils, we have at once all the elements for a comparison of the electro-static and electro-magnetic action of the same battery. That is, the results of Professor Maxwell's experiments give a direct value of the relation between electro-static and electro-magnetic units of electro-motive force.

The following are a series of values of v given by Professor Maxwell :—

	$2{\cdot}8591 \times 10^{10}$
	$2{\cdot}8430$,,
	$2{\cdot}8886$,,
	$2{\cdot}8686$,,
	$2{\cdot}8910$,,
	$2{\cdot}8850$,,
	$2{\cdot}8762$,,
	$2{\cdot}8795$,,
	$2{\cdot}8735$,,
	$2{\cdot}8752$,,
	$2{\cdot}8709$,,
	$2{\cdot}9474$,,
Mean value of v	$2{\cdot}8798 \times 10^{10}$

or

288,000,000 metres per second.

or

179,000 statute miles per second.

The "probable error" is about one-sixth per cent.

Ayrton and Perry's Determination.*

At the Dublin meeting of the British Association in 1878 Professor W. E. Ayrton gave an account of a determination of v, which had been recently made in Japan by Professor Perry and himself.

The plan adopted by them was to measure the capacity of an air-condenser, each plate of which was 1323·14 square centimetres in area, both electro-statically and electro-magnetically.

* Report, Brit. Assoc., Dublin, 1878, p. 487; or Phil. Mag., 1879, i. p. 277, and Jour. Soc. Tel. Engineers, May, 1879.

The electro-static capacity was ascertained by linear measurement of the condenser, while the electro-magnetic capacity was determined by noting the first swing on discharging the condenser through a special form of *Balistic* galvanometer devised by them for the purpose with forty magnets in two spherical masses so as to have great sensibility and exceedingly little air-damping (see vol. i. page 240).*

The source of electricity was 382 new Daniell's cells. To determine the relation of battery and galvanometer constants, a known fraction of the current was sent through the galvanometer directly, by which means, from the limit of the swing obtained on discharging the condenser through the galvanometer, its capacity in electro-magnetic measure could be determined independently of the absolute strength of the magnetic field in the laboratory.

The required velocity v was the inverse ratio of the square roots of the two determinations of capacity,† and Messrs. Ayrton and Perry claim that their method has the advantage that the formula for reduction of the observations involves only the *square root* of a resistance, so that if any unknown error existed in the resistance coils, only the *square root* of that error would be introduced into the result, whereas, in the methods previously described, the error in v is directly proportional to that in the coils; and also that only *one* accurate electrical measuring instrument—a balistic galvanometer—is employed, whereas the other methods required two, such as an absolute electrometer combined with a galvanometer, &c.

The following results were obtained on three different days :—

1878.	v
June 18	$2{\cdot}974 \times 10^{10}$
June 23	$2{\cdot}995 \times 10^{10}$
June 25	$2{\cdot}972 \times 10^{10}$
Mean of 98 discharges of the air condenser .	$2{\cdot}980 \times 10^{10}$

HOCKIN'S EXPERIMENTS.

On August 26, 1879, Mr. Charles Hockin read before the British Association a "Note on the Capacity of a certain Condenser and on the Value of v."‡

The method used for the determination of v was identical with that of Messrs. Ayrton and Perry.

* The periodic time of swing was equal to about 42 seconds.

† For one electro-magnetic unit of capacity equals v^2 electro-static units.

‡ Report, Brit. Assoc., Sheffield, 1879, p. 285.

The result obtained was

$$v = 2{\cdot}988 \times 10^{10} \text{ centims. per second.}$$

PHYSICAL NATURE OF v.

To obtain a physical conception of this velocity, let us consider a fact which was predicted from theory by Professor Maxwell,* and afterwards verified experimentally by Professor Rowland.†

Professor Maxwell predicted that if a statically-charged body could be moved with the velocity of an electric current, it would act in all respects as an electric current carrying the same quantity of electricity per second.

From this it follows that if two similarly-charged bodies be placed near together, and moved rapidly along two parallel lines, in the same direction and with the same velocity, that at a certain velocity their electro-magnetic attraction would exactly balance their electro-static repulsion, and that there would be no force between them.

But the electro-static force depends (for a given distance) only on the number of electro-static units of quantity with which the bodies are charged.

The electro-magnetic force depends on the number of static units of quantity multiplied by the velocity of motion.

Let us call

Electro-static force	$\overline{\mathrm{S\,F}}$
Electro-magnetic force	$\overline{\mathrm{M\,F}}$
Velocity of Motion	V

We have

$$\overline{\mathrm{SF}} = \mathrm{Q\,Q'} \quad . \quad . \quad . \quad . \quad (1)$$

$$\overline{\mathrm{MF}} = \mathrm{Q\,Q'\,V} \quad . \quad . \quad . \quad (2)$$

But when $\overline{\mathrm{S\,F}}$ is equal to $\overline{\mathrm{M\,F}}$, the ratio of the numbers expressing the two quantities is inversely as the ratio of their units.‡

Hence

$$\overline{\mathrm{MF}} = v\,\overline{\mathrm{SF}} \quad . \quad . \quad (3)$$

and we may write

$$\overline{\mathrm{SF}} = \mathrm{Q\,Q'} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and from (2) and (3)

$$v\,\overline{\mathrm{SF}} = \mathrm{Q\,Q'\,V} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Dividing (5) by (1) we have

* "Electricity," 769, vol. ii. p. 369.

† See next page.

‡ Similarly, if 10 yards equal 30 feet, the ratio of the numbers is 1 to 3, and therefore that of the units 3 to 1.

$$v = V,$$

or the ratio of the units equals the velocity with which an electrified body must be moved to make it act as a current conveying the same quantity of electricity per second.

Rowland's Experiments.

Professor Maxwell has pointed out that, though it is of course impossible to move a charged body with the velocity of electricity, yet that it might be possible to move it fast enough to get an appreciable magnetic effect.

On June 15, 1875, Professor Helmholtz read before the Berlin Academy* an account of some experiments made by Professor Rowland on the magnetic effect of a statically-charged body in motion.

In these experiments a gilt ebonite disc, 21·1 centims. in diameter, was revolved sixty-one times per second near an astatic needle. The disc was electrified by connecting it to a charged Leyden jar. The electro-static potential was determined by seeing what length of spark the charge would give, and comparing the result with Sir William Thomson's tables of the "electro-motive force required to produce a spark."†

The magnetic effect was determined by observing the deflection of the needles by means of a mirror and scale in the ordinary manner.

Having observed the magnetic effect, Professor Rowland calculates what it would have been if v had had the values given by Weber and Maxwell respectively, and he found that the observed number came between the two calculated numbers.

Here Professor Rowland left his results, as they were not undertaken as a measurement of v. But by a simple process of interpolation between the magnetic effects, calculated from Maxwell's and Weber's v respectively, we can find what value of v would have given exactly the observed magnetic effect. The result of the calculation is

$$v = 3{\cdot}0448 \times 10^{10} \text{ centims. per second.}$$

In my account of the above experiments I have omitted the

* Berlin Monatsbericht, 1876, p. 211, translated Phil. Mag., September, 1876, p. 233.

† Vol. ii. p. 64.

details of numerous corrections, &c., which were applied by Professor Rowland.

SUMMARY.

We have for v the following values :—

Experimenter.	v 10 centims. per second.
Weber and Kohlrausch . . .	3·1074
Thomson	2·825
Maxwell	2·8798
McKichan	2·93
Ayrton and Perry	2·980
Hockin	2·988
(from) Rowland	3·0448
Mean of the four last . . .	2·9857

An examination of the details of the experiments shows that the four last sets are much more trustworthy than the earlier determinations, and I have therefore adopted, as the most probable value of v,

$$2{\cdot}9857 \times 10^{10} \text{ centims., or } 185{,}521 \text{ miles per second.}$$

PART IV.

ELECTRO-OPTICS.

A PHYSICAL TREATISE

ON

ELECTRICITY AND MAGNETISM.

Part IV.

RELATIONS BETWEEN ELECTRICITY AND LIGHT OR, "ELECTRO-OPTICS."

CHAPTER XLVI.

MAGNETIC ROTATION OF POLARIZED LIGHT.*

PRELIMINARY.

ORDINARY light consists of vibrations taking place always in planes at right angles to the direction of the ray, but in all directions in those planes. That is, if the ray travels along the axle of a wheel, the vibrations composing it are all in the plane of the wheel, but are executed along any or all of the spokes.

The effect of reflecting light at certain angles from certain substances, or of passing it through certain crystalline substances, is to cause all the vibrations to take place in the same direction—that is, along one spoke of the wheel and the spoke opposite to it,

The light is then said to be polarized. Now if the wheel, without being rotated, be slid along the axle, the spoke along which the vibrations take place will trace out a plane.

When no rotative force is applied to the polarized light, the

* The student who is ignorant of the elements of the theory of polarized light is recommended to read "The Polarization of Light," by Wm. Spottiswoode, Pres. R.S., &c. Nature Series (Macmillan).

vibrations all take place in this plane, and the light is said to be "plane-polarized."

If we twist the reflector or crystal, which we use as a polarizer, round the direction of the ray as axis, we shall shift this plane in the same way as if we cause the wheel to turn on its axis and so shift the spoke along which the vibrations take place; but, when the wheel is slid along the axis, this spoke will still trace out a plane, only that plane will not be the same as before. That is, if we turn the polarizing mirror or crystal, we turn the plane of polarization, but the light still remains plane-polarized.

We cannot detect by the eye in what plane light is polarized, or indeed whether or not it is polarized at all. In order to do so we have to take advantage of the following natural law:—

Transparent bodies which have the power of polarizing light in any given plane are opaque to light already polarized in a plane at right angles to that plane; and reflecting surfaces which have the power of polarizing light in a given plane will not reflect light which, when it falls on them, is already polarized in a plane at right angles to that plane.

Thus, to determine in what plane light is polarized, we have only to take a crystal which has the power of polarizing light in a certain plane fixed with regard to its axis, and to turn it round till the light is extinguished.

We then know that the light is polarized in a plane at right angles to that plane in the crystal.

Natural Rotation.

Certain natural substances, such as oil of turpentine, creosote, &c., possess the power of "rotating the plane of polarization;" that is, if a horizontal beam of light, polarized in a horizontal plane, be sent through a tube filled with one of these substances, its plane of polarization, on emergence, will no longer be horizontal, but will be inclined on one side or the other of the horizontal, according to the nature of the substance.

The amount of inclination for the same substance depends on the length of the substance travelled through.

Faraday's Discovery of Magnetic Rotation.

Faraday discovered that if a piece of a particular kind of glass known as "heavy glass" is placed between the poles of an

electro-magnet, and a ray of polarized light sent through it from pole to pole, the plane of polarization is rotated. That is, if the light be supposed to go in, in a horizontal plane, it emerges, still plane-polarized, in a plane inclined to the horizontal. The direction of the inclination depends on the polarity of the magnet; if this be reversed, by reversing the current, the direction of the rotation is changed. Faraday afterwards found that many other substances could produce the same effect when magnetized.

Thus far the magnetic phenomenon appears to be analogous to the phenomenon of rotation by oil of turpentine, &c. There is, however, a very important difference between the two cases.

DIFFERENCE BETWEEN MAGNETIC AND NATURAL ROTATION.

If, instead of permitting the light to emerge, we let it fall perpendicularly on a mirror placed at the end of the column of turpentine or glass, and be reflected back, we shall find that, *in the case where the rotation is produced by the magnetic force, the amount of rotation is doubled; while in the case where the rotation is produced by the natural power of the substance, the rotation is annulled;* and further, if by silvering both ends of, the heavy glass, or of the tube containing the oil cf turpentine, we cause the light to pass backward and forward any number of times (fig. 239), we shall find that, in the case of the magnetic rotation, the rotation is equal to as many times the original rotation as the light passes through the substance; while in the

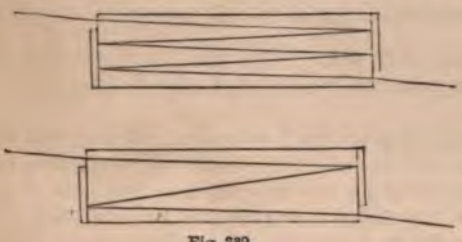


Fig. 239.

case of the natural rotation, it is zero or equal to the original rotation, according to whether the light passes through the substance an even or an odd number of times.

A mechanical illustration may assist us to understand this. Let us, as before, represent the plane of polarization by the direction of the spoke of a wheel, and let us slide the wheel backward

and forward on the axis, and cause it to rotate at the same time so that the spoke is always in the plane of polarization at the point where the wheel is on the axis. The case of natural rotation will then be illustrated by considering the turning of the wheel to be produced by the guiding action of a spiral or long screw thread cut on the axis. Thus, as the wheel moves along, the spoke traces out a twisted surface, while, when the wheel is slid back again, the spoke comes back along the same surface.

The case of magnetic rotation, however, is illustrated by considering the wheel *to be turned constantly in the same direction by some external force,* such as the pulling of a string wound round its circumference while the wheel is slid backward and forward. Let us suppose as before that the spoke always lies in the plane of polarization; the twisted surface traced out by it will now be different, as, on the wheel beginning to slide back along the axis, the spoke will not return on its old path, but will trace out a new surface whose twist is equal and opposite to the twist of the first surface.

Faraday's Paper.

Faraday communicated his discovery to the Royal Society on November 6, 1845, in a paper entitled,—

"On the Magnetization of Light and the Illumination of Magnetic Lines of Force: i. Action of Magnets on Light; ii. Action of Electric Currents on Light; iii. General Considerations."*

He commences his paper as follows :—

* Phil. Trans., 1846, p. 1. "Exp. Res.," 2146, vol. iii. p. 1.

The following footnote was appended by Faraday to the title of his paper :—

"The title of this paper has, I understand, led many to a misapprehension of its contents, and I therefore take the liberty of appending this explanatory note :—Neither accepting nor rejecting the hypothesis of an ether, or the corpuscular, or any other view that may be entertained of the nature of light; and, as far as I can see, nothing being really known of a ray of light more than of a line of magnetic or electric force, or even of a line of gravitating force, except as it and they are manifest in and by substances; I believe that in the experiments I describe in the paper, light has been magnetically affected, i.e. that that which is magnetic in the forces of matter has been affected, and in return has affected that which is truly magnetic in the force of light: by the term magnetic I include here either of the peculiar exertions of the power of a magnet, whether it be that which is manifest in the magnetic or the diamagnetic class of bodies. The phrase,

"ACTION OF MAGNETS ON LIGHT.

"I have long held an opinion, almost amounting to conviction, in common, I believe, with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or, in other words, are so directly related and mutually dependent, that they are convertible, as it were, one into another, and possess equivalents of power in their action.* In modern times, the proofs of their convertibility have been accumulated to a very considerable extent, and a commencement made of the determination of their equivalent forces.

"This strong persuasion extended to the powers of light, and led, on a former occasion, to many exertions, having for their object the discovery of the direct relation of light and electricity, and their mutual action in bodies subject jointly to their power; but the results were negative and were afterwards confirmed in that respect by Wartmann.

"These ineffectual exertions, and many others which were never published, could not remove my strong persuasion derived from philosophical considerations; and, therefore, I recently resumed the inquiry by experiment in a most strict and searching manner, and have at last succeeded in *magnetizing and electrifying a ray of light, and in illuminating a magnetic line of force.* These results, without entering into the detail of many unproductive experiments, I will describe as briefly and clearly as I can."

ARRANGEMENT OF THE EXPERIMENTS.

"A ray of light issuing from an Argand lamp was polarized in a horizontal plane by reflection from a surface of glass, and the polarized ray passed through a Nicol's eye-piece revolving

'Illumination of the lines of magnetic force,' has been understood to imply that I had rendered them luminous. This was not within my thought. I intended to express that the line of magnetic force was illuminated as the earth is illuminated by the sun, or the spider's web illuminated by the astronomer's lamp. Employing a ray of light, we can tell *by the eye* the direction of the magnetic lines through a body; and, by the alteration of the ray and its optical effect on the eye, can see the course of the lines just as we can see the course of a thread of glass, or any other transparent substance rendered visible by the light: and this is what I meant by *illumination*, as the paper fully explains.—December 15, 1845. M. F."

* "Exp. Res.," 57, 366, 376, 877, 961, 2071.

on a horizontal axis, so as to be easily examined by the latter. Between the polarizing mirror and the eye-piece two powerful electro-magnetic poles were arranged, being either the poles of a horse-shoe magnet, or the contrary poles of two cylinder magnets; they were separated from each other about two inches in the direction of the line of the ray, and so placed that, if on the same side of the polarized ray, it might pass near them; or, if on contrary sides, it might go between them, its direction being always parallel, or nearly so, to the magnetic lines of force. After that, any transparent substance placed between the two poles would have, passing through it, both the polarized ray and the magnetic lines of force at the same time and in the same direction.

"A piece of heavy glass, about two inches square and 0·5 of an inch thick, having flat and polished edges, was placed between the poles (not as yet magnetized by the electric current) so that the polarized ray should pass through its length; the glass acted as air, water, or any other indifferent substance would do; and if the eye-piece were previously turned into such a position that the polarized ray was extinguished, or rather the image produced by it rendered invisible, then the introduction of this glass made no alteration in that respect. In this state of circumstances the force of the electro-magnet was developed, by sending an electric current through its coils, *and immediately the image of the lamp flame became visible, and continued so as long as the arrangement continued magnetic.* On stopping the electric current, and so causing the magnetic force to cease, the light instantly disappeared; these phenomena could be renewed at pleasure, at any instant of time, and upon any occasion, showing a perfect dependence of cause and effect. The voltaic current which was used upon this occasion was that of five pair of Grove's construction, and the electro-magnets were of such power that the poles would singly sustain a weight of from twenty-eight to fifty-six or more pounds. A person looking for the phenomenon for the first time would not be able to see it with a weak magnet.

"The character of the force thus impressed upon the glass is that of *rotation;* for when the image of the lamp-flame has thus been rendered visible, revolution of the eye-piece to the right or left, more or less, will cause its extinction; and the further motion of the eye-piece to the one side or the other of this posi-

tion will produce the reappearance of the light, and that with complementary tints, according as this further motion is to the right or left hand.

"When the pole nearest to the observer was a marked pole, i.e. the same as the north-pointing end of a magnetic needle, and the further pole was unmarked, the rotation of the ray was left-handed;* for the eye-piece had to be turned to the left hand, or in the opposite direction to the hands of a clock, to overtake the ray and restore the image to its first condition. When the poles were reversed, which was instantly done by changing the direction of the electric current, the rotation was changed also and became right-handed, the alteration being to an equal degree in extent as before. The direction was always the same for the same *line of magnetic force*.

"When the diamagnetic was placed in the numerous other positions, which can easily be conceived, about the magnetic poles, results were obtained more or less marked in extent, and very definite in character, but of which the phenomena just described may be considered as the chief example.

"The same phenomena were produced in the silicated borate of lead (heavy glass) by the action of a good ordinary steel horse-shoe magnet, no electric current being now used. The results were feeble, but still sufficient to show the perfect identity of action between electro-magnets and common magnets in this their power over light.

"Two magnetic poles were employed endways, i.e. the cores of the electro-magnets were hollow iron cylinders, and the ray of polarized light passed along their axes and through the diamagnetic placed between them: the effect was the same.

"One magnetic pole only was used, that being one end of a powerful cylinder electro-magnet. When the heavy glass was beyond the magnet, being close to it but between the magnet and the polarizing reflector, the rotation was in one direction, dependent on the nature of the pole; when the glass was on the near side, being close to it, but between it and the eye, the rotation for the same pole was in the contrary direction to what it was before; and when the magnetic pole was changed, both these directions were changed with it. When the heavy glass was

* I have corrected what is evidently an accidental error in the direction of the rotation as given in Faraday's paper.

placed in a corresponding position to the pole, but above or below it, so that the *magnetic curves* were no longer passing through the glass parallel to the ray of polarized light, but rather perpendicular to it, then no effect was produced. These particularities may

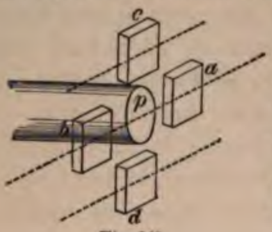


Fig. 240.

be understood by reference to fig. 240, where *a* and *b* represent the first positions of the diamagnetic, and *c* and *d* the latter positions, the course of the ray being marked by the dotted line. If also the glass were placed directly at the end of the magnet, then no effect was produced on a ray passing in the direction here described, though it is evident, from what has been already said, that a ray passing *parallel* to the magnetic lines through the glass so placed would have been affected by it.

"Magnetic lines, then, in passing through silicated borate of lead (heavy glass), and a great number of other substances, cause these bodies to act upon a polarized ray of light when the lines are parallel to the ray, or in proportion as they are parallel upon it: if they are perpendicular to the ray, they have no action upon it." (Faraday calls the glass and other substances "diamagnetics.") "They give the diamagnetic the power of rotating the ray; and the *law* of this action on light is, that if a magnetic line of force be *going from* a south-pointing or "plain" pole or *coming* from a north-pointing or "marked" pole along the path of a polarized ray coming to the observer, it will rotate that ray to the right hand; or that if such a line of force be coming from a south-pointing pole or going from a north-pointing pole, it will rotate such a ray to the left hand.

"If a cork or a cylinder of glass fig. 241 representing the diamagnetic be marked at its ends with the letters N and S, to

Fig. 241.

represent the direction in which the poles of the magnet would point if it was suspended, the line joining these letters may be considered as a magnetic line of force; and further, if a line be traced round the cylinder with arrow-heads on it to represent direction, as in the figure, such a simple model, held up before the eye, will express the whole of the law, and give every position and consequence of direction resulting from it. If a watch be considered as the diamagnetic, the south-

pointing pole of a magnet being imagined against the face, and a north-pointing pole against the back, then the motion of the hand will indicate the direction of rotation which a ray of light undergoes by magnetization."

Perhaps the simplest way to remember the direction is to note that *in all diamagnetic media the plane of polarization is rotated in the same direction as that in which a current would have to circulate round the ray to produce the existing magnetism.*

Faraday next "proceeds to the different circumstances which affect, limit, and define the extent and nature of this new power of action on light.

"In the first place, the rotation appears to be in proportion to the extent of the diamagnetic through which the ray and the magnetic lines pass. No addition or diminution of the heavy glass on the *side* of the course of the ray made any difference in the effect of that part through which the ray passed.

"The power of rotating the ray of light *increased* with the intensity of the magnetic lines of force; and it appears to be directly proportionate to the intensity of the magnetic force.

"Other bodies, besides the heavy glass, possess the same power of becoming, under the influence of magnetic force, active on light. When these bodies possess a rotative power of their own, as is the case with oil of turpentine, sugar, tartaric acid, tartarates, &c., the effect of the magnetic force is to add to, or subtract from, their specific force, according as the natural rotation and that induced by the magnetism is right or left handed."

Faraday notes that he could not perceive that this power was affected by any degree of motion which he was able to communicate to the diamagnetic, whilst jointly subject to the action of magnetism and light.

"The electro-helices without the iron cores were very feeble in power, and indeed hardly sensible in their effect. With the iron cores they were powerful, though no more electricity was passing through the coils than before. This shows, in a very simple manner, that the phenomena exhibited by light under these circumstances is directly connected with the magnetic form of force supplied by the arrangement. Another effect which occurred illustrated the same point. When the contact at the voltaic battery is made, and the current sent round the electro-

magnet, the image produced by the rotation of the polarized ray does not rise up to its full lustre immediately, but increases for a couple of seconds, gradually acquiring its greatest intensity; on breaking the contact, it sinks instantly and disappears apparently at once. The gradual rise in brightness is due to the *time* which the iron core of the magnet requires to evolve all that magnetic power which the electric current can develope in it; and as the magnetism rises in intensity, so does its effect on the light increase in power; hence the progressive condition of the rotation."

Faraday could not "find that the heavy glass, when in this state, i.e. with magnetic lines of force passing through it, exhibits any increased degree, or has any specific magneto-inductive action of the recognized kind." He "placed it in large quantities, and in different positions, between magnets and magnetic needles, having at the time very delicate means of appreciating any difference between it and air, but could find none."

"Using water, alcohol, mercury, and other fluids, contained in very large, delicate, thermometer-shaped vessels," he "could not discover that any difference in volume occurred when the magnetic curves passed through them."

Faraday observed that many other substances besides heavy glass exhibited this property of rotating a ray when magnetized. Crystals generally show but small effect.

Liquids.

Faraday found that every liquid which he tried showed the effect in a greater or less degree.

Gases.

Faraday was unable to detect any effect with gases.

Bodies having Natural Rotation.

In the cases where bodies had previously a natural rotative power in either direction, the superinduced magnetic rotation was according to the general law, and without reference to the previous power of the body.

Action of Electric Currents on Light.

Faraday found, as we should expect, that the action of an electric current was the same as that of its equivalent magnet, or that if any substance having magnetic rotative power were placed inside a helix, that a ray of light passing through the

substance along the helix, would be rotated when the current passed; the direction of rotation depending on the direction of the current.

In this case the light did not appear gradually but instantaneously.

Solids were made in the form of long rods with polished ends, and placed inside the helix.

Liquids were contained in glass tubes with flat glass ends.

Law of Action.

It was found that, in all the substances which Faraday examined, the plane of polarization was twisted in the same direction as the current in the helix was rotating.

By substituting for the helix its equivalent magnet we shall see that this agrees with the direction of rotation caused by a magnet.

General Conclusions.

The following are Faraday's general conclusions:—

"Thus is established, I think, for the first time, a true direct relation and dependence between light and the magnetic and electric forces; and thus a great addition made to the facts and considerations which tend to prove that all natural forces are tied together, and have one common origin. It is, no doubt, difficult in the present state of our knowledge to express our expectation in exact terms; and though I have said that another of the powers of nature is, in these experiments, directly related to the rest, I ought, perhaps, rather to say that another form of the great power is distinctly and directly related to the other forms; or that the great power manifested by particular phenomena in particular forms is here further identified and recognized by the direct relation of its form of light to its forms of electricity and magnetism.

"The relation existing between *polarized* light and magnetism and electricity is even more interesting than if it had been shown to exist with common light only. It cannot but extend to common light; and, as it belongs to light made, in a certain respect, more precise in its character and properties by polarization, it collates and connects it with these powers, in that duality of character which they possess, and yields an opening, which before was wanting to us for the appliance of these powers to the investigation of the nature of this and other radiant agencies.

"Referring to the conventional distinction before made, it may be again stated that it is the magnetic lines of force *only* which are effectual on the rays of light, and they *only* (in appearance) when parallel to the ray of light, or as they tend to parallelism with it. As, in reference to matter not magnetic after the manner of iron, the phenomena of electric induction and electrolyzation show a vast superiority in the energy with which electric forces can act as compared to magnetic forces, so here, in another direction and in the peculiar and correspondent effects which belong to magnetic forces, they are shown, in turn, to possess great superiority, and to have their full equivalent of action on the same kind of matter.

"The magnetic forces do not act on the ray of light directly and without the intervention of matter, but through the mediation of the substance in which they and the ray have a simultaneous existence; the substances and the forces giving to and receiving from each other the power of acting on the light. This is shown by the non-action of a vacuum or of air or gases; and it is also further shown by the special degree in which different matters possess the property. That magnetic force acts upon the ray of light always with the same character of manner and in the same direction* independent of the different varieties of substance, or their states of solid or liquid, or their specific rotative force, shows that the magnetic force and the light have a direct relation; but that substances are necessary, and that these act in different degrees, shows that the magnetism and the light act on each other through the intervention of the matter.

"Recognizing or perceiving *matter* only by its powers, and knowing nothing of any imaginary nucleus, abstract from the idea of these powers, the phenomena described in this paper much strengthen my inclination to trust in the views I have on a former occasion advanced in reference to its nature.†

"It cannot be doubted that the magnetic forces act upon and affect the internal constitution of the diamagnetic just as freely in the dark as when a ray of light is passing through it; though the phenomena produced by light seem, as yet, to present

* It has since been shown by Verdet that this is not the case. Paramagnetic substances rotate the light in a direction opposite to diamagnetics. See vol. ii., p. 225.

† "Exp. Res.," vol. ii., p. 284; or Phil. Mag., 1844, vol. xxiv., p. 136.

the only means of observing this constitution and the change. Further, any such change as this must belong to opaque bodies, such as wood, stone, and metal; for as diamagnetics, there is no distinction between them and those which are transparent. The degree of transparency can at the utmost, in this respect, only make a distinction between the individuals of a class.

"If the magnetic forces had made these bodies magnets, we could by light have examined a transparent magnet; and that would have been a great help to our investigation of the forces of matter. But it does not make them magnets,* and therefore the molecular condition of these two bodies, when in the state described, must be specifically distinct from that of magnetized iron, or other such matter, and must be *a new magnetic condition;* and as the condition is a state of tension (manifested by its instantaneous return to the normal state when the magnetic induction is removed), so the *force* which the matter in this state possesses, and its mode of action, must be to us a *new magnetic force* or *mode of action* of matter.

"For it is impossible, I think, to observe and see the action of magnetic forces, rising in intensity upon a piece of heavy glass or a tube of water, without also perceiving that the latter acquire properties which are not only *new* to the substance, but are also in subjection to very definite and precise laws, and are equivalent in proportion to the magnetic forces producing them.

"Perhaps this state is a state of *electric tension tending to a current;* as in magnets, according to Ampère's theory, the state is a state of *current.* When a core of iron is put into a helix, everything leads us to believe that currents of electricity are produced within it, which rotate or move in a plane perpendicular to the axis of the helix. If a diamagnetic be placed in the same position, it acquires power to make light rotate in the same plane. The state it has received is a state of tension, but it has not passed on into currents, though the acting force and every other circumstance are the same as those which do produce currents in iron, nickel, cobalt, and such other matters as are fitted to receive them. Hence the idea that there exists in diamagnetics, under such circumstances, a tendency to currents, is consistent with all the phenomena as yet described, and is further strengthened by the

* It has since been shown that it makes them diamagnets. See vol. ii. p. 20, "Tyndall on Diamagnetic Polarity."

fact that, leaving the loadstone or the electric current, which by inductive action is rendering a piece of iron, nickel, or cobalt magnetic, perfectly unchanged, a mere change of temperature will take from these bodies their extra power, and make them pass into the common class of diamagnetics."

FURTHER INVESTIGATIONS.

The subject was next studied by Weidemann, who experimented on liquids subjected to the direct action of currents carried in helices.

VERDET'S EXPERIMENTS.

In 1852 M. Verdet* commenced to investigate the subject, and it is to him after Faraday that we owe the greater part of our knowledge of it. He first combined quantitative measurements with the use of powerful magnetic forces. In most of his experiments he used a large electro-magnet with iron cores, and, by the use of perforated poles, he was enabled to cause a beam of light to pass along the line of maximum magnetic force. In his first investigation the iron cylinders forming the cores of his electro-magnet were perforated longitudinally.

Fig. 242 shows the arrangement of M. Verdet's apparatus.

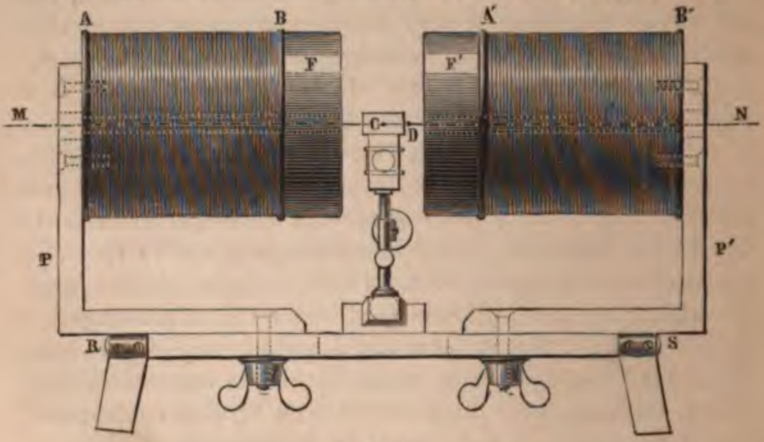


Fig. 242.

* "Œuvres de Verdet," tome i. p. 112. Paris: Masson, 1872. All extracts from M. Verdet's writings are taken from the edition of his collected works, published by his pupils in 1872-75. It has been considered more convenient to give references to the collected works than to the journals in which the papers were originally published.

The cylinders A B, A′ B′ being placed with their axes in the same horizontal line, a beam of light M N could be sent through them, and through a piece of glass or other transparent medium, placed in the small space left between their near ends. The exterior ends were connected by a massive rod of soft iron P R S P′ bent into the shape of three sides of a rectangle.

It being very important, as will be seen immediately, that the glass and the space in its immediate neighbourhood should be contained in a field of uniform magnetic force, thick iron discs F F′, perforated at their centres, were placed upon the near ends of the iron cores.

MEASUREMENT OF THE INTENSITY OF THE MAGNETIC FIELD.

Having secured a field of magnetic force sensibly uniform over a considerable space, M. Verdet inserted in it, side by side, the transparent body on which he was about to experiment, and the apparatus C D which he used for determining the strength of the field.

The theory of this latter was founded on the fact that the whole, or integral, current due to the motion of a given wire in a magnetic field (such current being measured by the extreme limit of the first swing of the galvanometer needle) depends only on the intensity of the magnetic field and the amount of the whole motion; but does not depend on the velocity of the motion when that velocity is considerable.

A little bobbin C (fig. 243) of silk-covered wire was constructed, and fixed so that it could be turned, by means of the handle B, through 90° round an axis, F G, at right angles to the axis of the bobbin.

The bobbin was 28 millims. external and 12 mm. internal diameter—15 mm. long. It was fixed on a little copper stand between the poles, so that the line round which it could be turned was at right angles to the line joining the poles, and passed midway between them. It could be raised and lowered by means of the handle D, and clamped by the screw H.

When the bobbin was turned, its axis moved from the vertical to the horizontal position, and *vice versâ*. While the current was flowing in the magnet coils, and while the optical effects were being observed, an assistant turned the bobbin suddenly through 90°, and the swing of the galvanometer needle was

observed. Of course a stop was used to limit the motion of the bobbin to exactly 90°. The swing of the galvanometer needle was then an accurate measure of the intensity of the magnetic

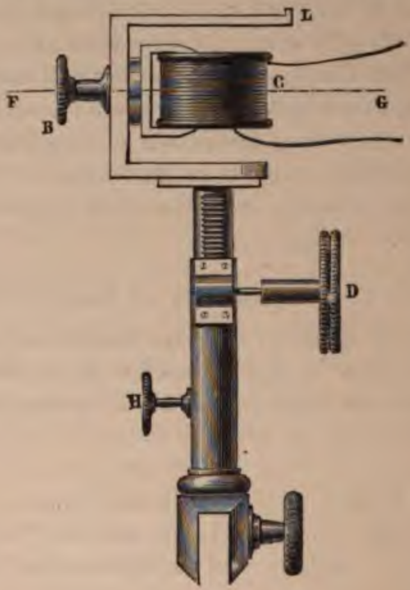


Fig. 243.

force to which the transparent medium was being subjected. It was, however, a measure in purely arbitrary units, although, with the same disposition of the apparatus, different measurements were strictly comparable with each other. If M. Verdet had removed his magnet, and caused the bobbin to be turned under the influence of the earth's magnetic force, on a day when the intensity of the latter was known, he would at once have reduced his measurements to absolute units. In his time, however, the importance of absolute measurement was hardly, if at all, recognized, and he did not make this observation.

Verdet experimented on Faraday's heavy glass, on common flint glass, and on bisulphide of carbon. The dimensions of the pieces of heavy glass that he used were—first, a parallelopiped of square base 40 millims. long, 13 mm. in the side, polished on its two bases, and on two opposite side faces.

Second, a rectangular parallelopiped 37·2 millims. by 26 mm. by 12·5 mm., polished on all six faces.

The flint glass was a parallelopiped 43·3 mm. long, 14·5 mm. in the side, polished on its two bases and on two of its side faces. By sending light either sideways or endways through the pieces, it could be made to traverse different lengths of glass. The bisulphide of carbon was contained sometimes in one, sometimes in the other of two tubes with glass ends whose lengths were respectively 44 and 31 mm. Some preliminary experiments showed that the action of the glass plates which formed the ends of these tubes was altogether insensible.

Rotation and Magnetic Strength.

The law which M. Verdet deduced from his first experiments is—

The rotation of the plane of polarization is proportional to the strength of the magnetic action—that is, if we divide the amount of rotation, observed in any experiment, by the strength of the magnetic field, as observed at the galvanometer in the same experiment, we shall find that, for the same substance, colour, and disposition of apparatus, the quotient is constant, whatever be the strength of the current used.

The following table is extracted from a great number of similar ones, given by M. Verdet, in order that the reader may judge for himself to what extent of accuracy the investigation has been carried :—

Experiments of Heavy Glass No. 2.*

Set III.

White light. Thickness, 37·2 m.

F	R	Q
148·25	6° 55′ 15″	2·80
116·37	5° 28′	2·82
107·00	5° 9′ 30″	2·89
92·87	4° 26′	2·84
89·37	4° 20′	2·91
83·50	4° 4′ 20″	2·93
59 37	2° 57′ 15″	2·98
	Mean	2·88

In these experiments R is double the rotation produced by the current—that is, it is the difference of the circle readings corresponding to the two directions of the current. F is the strength

* Verdet, tom. i., p. 137.

of the magnetic field as measured by the induction apparatus. Q equals $\frac{R}{F}$; that is, it equals the ratio of the rotation, to the magnetic force producing it. We see that the various values of Q are almost absolutely constant. Every further refinement in experimentation causes the various values of this ratio to agree more and more closely with each other. Experiments on homogeneous light give much more accurate results than experiments on white light, for, as no two colours are equally rotated by the same magnetic force, the rotation of white light simply means the rotation of the mean, or of the most prominent colour of those which compose it. Any small accidental discolouration of the medium may considerably alter the mean rotation, by altering the colour on which the chief effect is observed.

M. Verdet goes on to say that his law holds, whatever be the position of the poles of the magnet, or their distance from the glass.

Thickness of Medium.

He next experimented on the effect of the thickness of the glass traversed, and finds that, *with the same magnetic intensity, the rotation is directly proportional to the thickness of the glass traversed by the light.* In making the experiment it was not possible to obtain the same intensity of magnetic field with two different thicknesses of glass; but it is obvious that, if the above law holds, the ratio Q of the rotation to the magnetic intensity should be proportional to the thickness of the glass.

In two of the experiments which Verdet gives, we have,

First with heavy glass,

$$Q = \frac{R}{F} = 2{\cdot}88 \text{ and } 1{\cdot}92,$$

when the thicknesses traversed were respectively 37·2 and 26 millims. Dividing the above ratios by the corresponding thicknesses, we have the quotients 0·077 and 0·074. A similar calculation from experiments on bisulphide of carbon gives quotients 0·056 and 0·055. In both cases there is as close an agreement as could reasonably be expected with the given experimental conditions.

Angle between Directions of Light and Magnetic Force.

The next point which was investigated was the effect of

inclining the light to the direction of magnetic force. The apparatus used for this purpose is shown in plan in fig. 244.

The glass and Nicols being fixed so that the light travelled

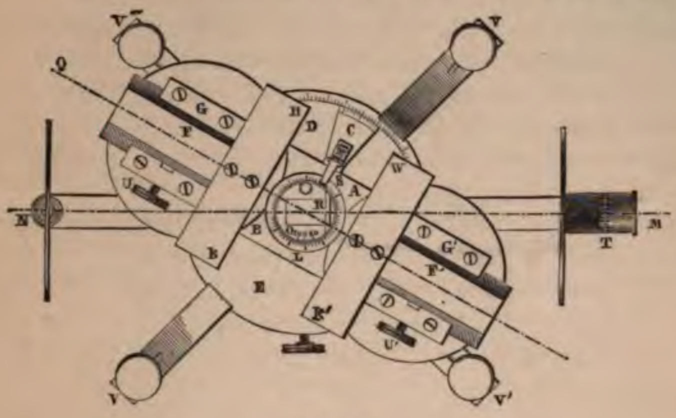


Fig. 244.

in a horizontal line, the magnet was so arranged that it could be turned round a vertical axis, and so cause the line of magnetic force to form a horizontal line making any desired angle with the direction of the light. For this purpose a magnet of ordinary horse-shoe form was used (shown in plan in fig. 244), the bobbins of which stood vertical, and had poles, H K, W K′, consisting of massive blocks of iron fixed on their cores. Horizontal slits in the iron poles permitted the light to pass, even when the angle between its direction and the axial line of the magnet was considerable. N is the polarizer, T M the analyzer. L and D are divided circles, by which the angle between the light and the magnetic axis can be measured. D is read by the vernier C. F F′ are slides for altering the distance between the poles. They move in guides G G′ and are clamped by screws U U′. V V′ are levelling screws. The law deduced from experiments with this apparatus is—

The rotation produced with a given intensity of magnetic field is simply proportional to the cosine of the angle between the direction of the light and the direction of the lines of magnetic force.

That is, it is proportional to the projection, on the line joining the poles, of the length of the medium traversed by the light.

Combining these three results we arrive at the simple general law that—

General Law.

For a given medium and colour, the rotation of the plane of polarization between any two points in the path of the ray is simply proportional to the difference of magnetic potential at those points.

For the difference of potential at two points in a magnetized substance depends simply and only on three things:

It is proportional (1) to the intensity of magnetization of the substance;

(2) To the cosine of the angle between the direction of magnetization and the line joining the two points; and

(3) To the distance between the two points.

Maxwell's Summary.

Prof. Clerk Maxwell * thus summarizes Faraday's and Verdet's results:—

"Art. 808. The angle through which the plane of polarization is turned is proportional—

"(1) To the distance which the ray travels within the medium: hence the plane of polarization changes continually from its position at incidence to its position at emergence.

"(2) To the intensity of the resolved part of the magnetic force in the direction of the ray.

"(3) The amount of the rotation depends on the nature of the medium. No rotation has as yet been observed when the medium was air or any other gas.†

"These three statements are included in the more general one —that the angular rotation is numerically equal to the amount by which the magnetic potential increases from the point at which the ray enters the medium to that at which it leaves it, multiplied by a co-efficient which for diamagnetic media is generally positive.

"809. In diamagnetic substances, the direction in which the plane of polarization is made to rotate is the same as the direction in which a positive current must circulate round the ray in order to produce a magnetic force in the same direction as that which actually exists in the medium."

The present writer was for nearly two years engaged, under Prof. Maxwell's direction, in determining the co-efficient mentioned in

* "Electricity," Art. 808, vol. ii. p. 400.

† See vol. ii. p. 237.

the last line of (Prof. Maxwell's) art. 808—that is, in "determining Verdet's constant in absolute units." An account of the experiments will be given later on.*

Different Media.

It is found that the amount of rotation which a given magnetic force produces on light of a given colour varies with the nature of the transparent medium—that is, that the co-efficient mentioned in the last line of Maxwell's art. (808) has different values for different media. As mentioned by Prof. Maxwell, it is generally positive for diamagnetic media; but for many ferromagnetic media it is negative. Verdet, in the memoir commencing at p. 163 of vol. i. of his works, has investigated what he calls the "Pouvoir rotatoire magnétique" of a large number of substances: that is, he has found a series of values of the co-efficient mentioned in Maxwell's article (808), all referred to the value of the co-efficient for distilled water, arbitrarily taken as unity. Owing to the impossibility of obtaining blocks of crystalline substances and salts, which did not act naturally on polarized light, all his experiments on such substances were made on solutions of them, chiefly aqueous solutions. He found that—

When a perfectly homogeneous medium (such as a liquid) is a mixture of two or more substances which do not act chemically on each other, the magnetic rotative power of the mixture is equal to the algebraic sum of the magnetic rotative powers of its constituents; the action of each being proportional to the quantity of it present.

In his early experiments this law was masked by his not remembering the fact that a pound of an aqueous solution does not generally contain a pound of water. If, for instance, a pound of salt be dissolved in 100 lbs. of water, a hundred pounds of the solution will only contain just over ninety-nine pounds of water. M. Verdet, however, almost immediately saw the necessity of this correction; and, when he had applied it, his experimental results bore out the above law as closely as could be desired.

Several physicists, notably M. Bertin, endeavoured to establish a relation between the magnetic rotative power of substances and their refractive indices; but at the time of the publication of Verdet's works no such relation could be said to be established.†

* Vol. ii. p. 228.

† A relation was found by M. H. Becquerel in 1877, see vol. ii., p. 233.

An interesting instance of the combined action of two substances, whose magnetic rotative powers are of opposite signs, is given by the action of an aqueous solution of perchloride of iron.

Of this Verdet says, "A very weak aqueous solution of this salt has a magnetic rotative power feebler than that of water. As we concentrate the solution, the rotative power diminishes; it reduces to zero, and ends by changing sign. After the change of sign, it increases up to the maximum of concentration. So a solution near that maximum, which contains 40 per cent. of perchloride, exercises on polarized light an action contrary to that of water and six or seven times greater."

The following table gives the "magnetic rotative powers" of various substances, that of distilled water being taken as 1·000.

Liquids.	Magnetic Rotative power.
Distilled water	1·000
Solution of borate of soda	1·000
" chloride of calcium	1·085
" carbonate of potash	1·050
" nitrate of lead	1·000
" chloride of magnesia	1·127
" sal ammoniac	1·184
" protochloride of tin	1·348
" chloride of zinc	1·341
" sal ammoniac	1·371
" carbonate of potash	1·087
" chloride of calcium	1·230
" protochloride of tin	1·525
" chloride of zinc	1·507
" protochloride of tin	2·047
" nitrate of ammonia	0·908
Chloride of carbon $C_2\,Ch_4$	1·264

I think it would have been better if M. Verdet had adopted bisulphide of carbon as his standard in preference to water.

My own experience of distilled water is that it is a most unsuitable substance for a standard, owing to its very feeble rotative power, and to the impossibility, not only of obtaining it chemically pure, but of even obtaining two specimens containing the same impurities. Bisulphide of carbon is much more suitable for this purpose, as it can easily be obtained nearly pure, and, owing to its very high rotative power, the magnetic actions of small impurities present in it introduce only a very small percentage of error.

EFFECTS OF THE COLOUR OF LIGHT ON THE ROTATION PRODUCED IN A GIVEN MEDIUM BY A GIVEN MAGNETIC FORCE.

It was for some time believed that with a given medium and magnetic force, the rotations varied inversely as the square of the wave-length of the light. I believe this was announced as a law by M. Edmond Becquerel.

Verdet, however, has shown that this law, though approximately, is not accurately true.

The following table * gives the relative values of the rotations corresponding to the five Fraunhofer lines, C, D, E, F, G, for various substances; the rotation for the ray E being taken as unity.

	C	D	E	F	G
Distilled water	0·63	0·79	1·00	1·20	1·55
Solution of chloride of calcium . .	0·61	0·80	1·00	1·19	1·54
Solution of chloride of zinc . .	0·61	0·78	1·00	1·19	1·61
Solution of protochloride of tin .	„	0·78	1·00	1·20	1·59
Essence of bitter almonds . .	0·61	0·78	1·00	1·21	„
Essence of anise seed . . .	0·58	0·75	1·00	1·25	„
Bisulphide of carbon . . .	0·60	0·77	1·00	1·22	1·65
Creosote of commerce . . .	0·60	0·76	1·00	1·23	1·69
Essence of laurus cassiæ . . .	0·59	0·74	1·00	1·23	„
Mean	0·604	0·772	1·00	1·213	1·605

The exact law of the inverse ratio of the square of the wave-length would give the rotations

C	D	E	F	G
0·64	0·80	1·00	1·08	1·50

We see from these figures that the magnetic rotation of the plane of polarization of rays of different colours follows approximately the law of the inverse ratio of the square of the wave-lengths.

The exact law of the phenomena is always such that the pro-

* Verdet, T. i., p. 206.

duct of the rotation, by the square of the length of the wave, continues to increase from the red to the blue end of the spectrum.

The substances for which this increment is most sensible are also those which have the greatest dispersive power.

Several mathematical explanations of this deviation have been attempted, but I am not aware that any of them agree very closely with experiment.

I will now pass on to some of the details of my determination in absolute measurement of the magnetic rotative power of bisulphide of carbon—that is, the "co-efficient" mentioned by Maxwell in the passage quoted, vol. ii., page 224.

VERDET'S CONSTANT.*—PLATE LI.

To determine this constant (Maxwell, Art. 808) it was necessary to know, in absolute measure, the difference of magnetic potential at the ends of the column of bisulphide of carbon which corresponded to a certain rotation of the plane of polarization of a ray of given wave-length.

For this purpose the bisulphide was enclosed in a tube with glass ends, about two feet long, which was placed horizontally inside a helix about one foot long (belonging to the electro-magnet, fig. 153, vol. ii. p. 13), and containing 35 lbs. weight of insulated copper wire. The tube thus projected at each end. Now the difference of magnetic potential due to a given current, at points on the axis of a helix and beyond its ends, can be calculated from the number of windings in the helix.

But the number of windings on the helix was not known. It was therefore determined by the process of comparison given in the Appendix to Chapter XXX., vol. ii. p. 6; it was found to be 1028·15.

To determine the strength of the currents used for the optical experiments, a small magnet and mirror was suspended outside the helix (which thus became its own galvanometer), and observed by a telescope and scale.

In order to determine the strength of a current in a helix from the deflection of a needle outside, it is necessary to know the sum of the areas of the windings of the helix. This was

* Phil. Trans. 1877, Part I., p. 7.

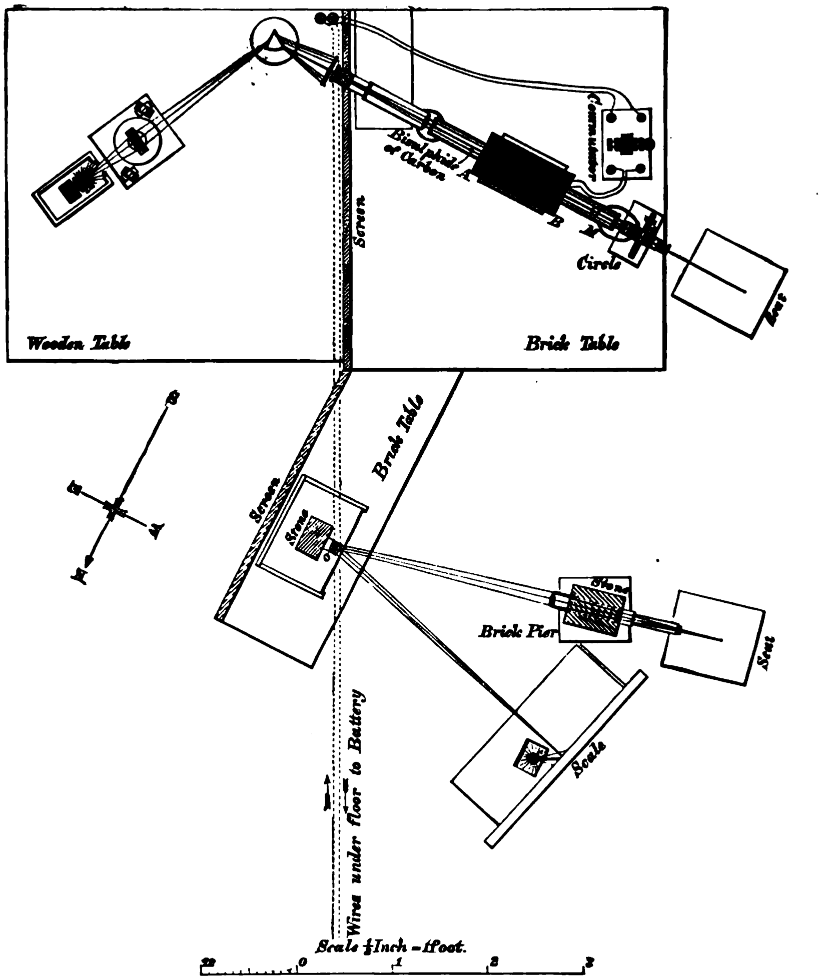


PLATE LI.—VERDET'S CONSTANT.

determined by the process given in vol. ii. p. 10, and found to be 77453 sq. centims.

The Light.

The light was obtained by throwing a spectrum from a powerful paraffin lamp and large bisulphide of carbon prism upon a card. A slit in the card admitted any desired colour into the Nicol. To localize the light, the lamp was removed and a spirit flame coloured with thallium was substituted. When the green line had been adjusted on the slit, the lantern, lens, and prism were clamped, and the lamp being replaced, the light admitted had the same wave-length as the thallium ray, for which

$$\lambda = (5{\cdot}349)\ 10^{-5} \text{ centims.*}$$

The light was polarized by a Nicol's prism, rendered parallel by a collimating lens, and analyzed by a Jellett's prism, which moved in a divided circle.

Plate LI. is a ground plan of the laboratory, showing the general arrangement of the apparatus.

The following was the arrangement of

The Jellett and Circle.

The Jellett prism † consisted of a piece of Iceland spar, of

Fig. 245.

Fig. 246.

which the ends were cut normal to the sides (fig. 245). It was then divided by a plane, making an angle of about 1° with the plane containing the two long diagonals. One half was reversed, and the two cemented together again (fig. 246).

* Watts' "Index of Spectra."

† This prism is described by Professor Jellett in the "Transactions of the Royal Irish Academy," vol. xxv., 1875, p. 371. Professor Jellett had the kindness to advise the author as to the form of his instrument best suited to this investigation.

The prism was mounted in a brass tube, and a diaphragm, with a hole of some 3 or 4 millims. diameter in it, through which polarized light was admitted, was placed across one end. On looking in from the other end of the prism, the hole was seen by the ordinary rays in the form of a circle divided by a line across it, the light of the two semicircles being polarized in planes making with each other an angle of about 2°.

The image of the hole formed by the extraordinary rays consisted of two semicircles, one to the right and the other to the left of this circle (fig. 247).

A second diaphragm hid the latter. Now when light that has passed through a Nicol is examined with this prism, and the latter turned so that the light of one half of the circle is extinguished, the other half is slightly illuminated. If the Jellett be turned through rather less than two degrees, the second half of the circle will become dark, and the first will be slightly illuminated.

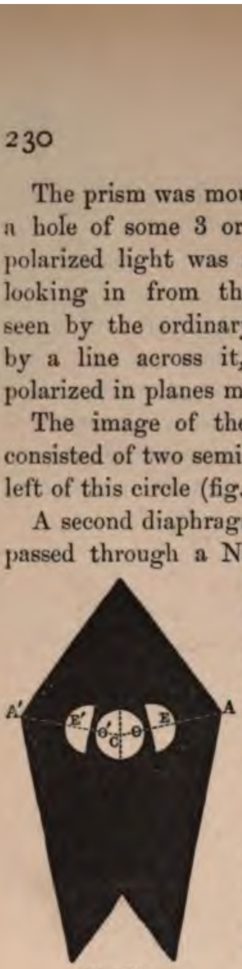


Fig. 247.

It is obvious that there is a position between these two where the illumination over the whole circle is uniform, and this position can be observed with considerable accuracy.

With the arrangements that were used in this research the probable error was about 1′.

The divided circle was made for this investigation by Mr. Browning, and is about 14 centims. diameter. The circle turns against two fixed verniers. It is divided on brass to 1°, and the verniers read to $\frac{1}{20}$°, i.e. to 3′. By estimation 1 can be read with perfect accuracy. It is moved by a screw of long pitch, working in a thread cut round its edge. This gives a sufficiently quick motion to enable changes in the illumination of any part of the field to be noted, and is yet capable of very delicate adjustment.

Earth's Horizontal Magnetic Force.

The values of the current deduced from the deflections of a magnetic needle only give the ratio of the current to the earth's horizontal magnetic force, H, at the time and place of obser-

vation. In order to know the absolute value, it is necessary to know H.

A continuous record of the variations of H is kept at Kew Observatory. To know H at the times and place of the optical experiments, the values of H at Kew were taken from the Kew tables and multiplied by the ratio of the force at Kew to the force at the author's laboratory at Pixholme, Dorking. To determine this ratio, the same magnet was vibrated at Kew and at Pixholme,* and after a somewhat elaborate series of corrections had been applied, it was found that

H at Pixholme = (·993366) H at Kew.

Formula.

Designating Verdet's constant by the letter ω we have the following formula for ω—

ω is the rotation of the polarized ray expressed in circular measure between two points in its path, whose magnetic potentials differ by unity; thus

$$\omega = \frac{\theta}{V_L - V_M}$$

where L and M are the ends of the tube and θ is the observed rotation of the plane of polarization expressed in circular measure.

Result.

The following was the final result of the experiments:—

The mean of the three numbers given below had afterwards to be multiplied by numbers depending on the area, number of windings, and length of tube. These numbers, however, are three separate determinations of the ratio which the rotation, R, of the plane of polarization bore to the strength of the current, which latter is proportional to H multiplied by the tangent of the deflection of the needle.

If the experiments had been absolutely correct, these three determinations would have been identical: as it is, we have—

$$\frac{2\,R}{H \tan \delta} = \begin{cases} 1 \quad . \quad . \quad . \quad 50118{\cdot}4 \\ 2 \quad . \quad . \quad . \quad 49767{\cdot}0 \\ 3 \quad . \quad . \quad . \quad 49538{\cdot}7 \end{cases} \quad \begin{matrix} \text{Mean} \\ 49808{\cdot}0 \end{matrix}$$

Extreme difference 0·6 per cent. from the mean.

* See vol. i., p. 174.

The actual rotations obtained in the experiments were

Set.	2 R*	Grove's cells.
2 . . .	11° 58′ 30″	5
3 . . .	13° 39′ 30″	6
1 . . .	15° 26′ 0″	7

We have finally, if ω be the rotation in bisulphide of carbon of the plane of polarization of the ray whose wave-length is

$$\lambda = (5\cdot349)\ 10^{-5}$$

between two points whose magnetic potentials differ by unity,

$$\omega = 3\cdot04763\ (10^{-6}).$$

The dimensions † of the constant are

$$[\omega] = [M^{-\frac{1}{2}} L^{-\frac{1}{2}} T],$$

for it is a number divided by a current, or, by what is of the same dimensions, a difference of magnetic potential.

This is Verdet's constant in absolute measure. For light of a given wave-length passing through a given substance, it is a fixed and definite physical quantity, depending only on the units of length, mass, and time.‡

ω, then, is defined to be Verdet's constant for the thallium ray in bisulphide of carbon, expressed in C.G.S. measure.

I may also here insert the result of a former paper of mine on the same subject. It is that for distilled water with white light.

$$\omega = 4\cdot496\ (10^{-6}).\S$$

I do not, however, attach much value to the result, as the different determinations are in the ratios of

7·563, 7·406, 8·295, 8·401, 6·916,

showing variations from the mean of ± 7 per cent., or giving only about $\frac{1}{10}$ of the accuracy of the present paper.

The methods used for determining the constants were also susceptible of less accuracy.

* 2 R is the difference of the circle readings when the current was reversed, and is, of course, double the rotation produced by it.

† See vol. ii., p. 180.

‡ The magnetic rotative power of bisulphide of carbon here comes in the same way as the specific heat of water comes into Joule's equivalent.

§ By an error in arithmetic this was printed 10^{-7} in the abstract of the paper published in the Proc. Roy. Soc., June, 1875.

Effect of Terrestrial Magnetism on Light.

In the "Comptes Rendus" for 1878,* M. Henri Becquerel pointed out that from these results we can calculate what would be the effect of the earth's magnetism on light in certain media.

If a canal one mile long were dug from north to south near Kew, and filled with bisulphide of carbon, a ray of the green polarized light experimented on entering at one end would, by the action of the earth's magnetism, have its plane of polarization twisted just 50°. If the canal had been full of distilled water, the twist would have been about $7\frac{1}{2}$°.

H. Becquerel's Experiments.

On July 10, 1876, M. Henri Becquerel presented to the Paris Academy of Sciences a paper entitled "Recherches Expérimentales sur la Polarization Rotatoire Magnetique." †

The first portion of the paper contains an account of a comparison between the magnetic rotative powers of different substances, that of bisulphide of carbon being taken as unity.

M. Becquerel's experiments were made on yellow and on red light, according to the colours of the substances used; but I think we may fairly assume that the ratio between different substances is approximately the same for all kinds of light.

On this assumption we can calculate from M. Becquerel's table, and from my measurement of Verdet's constant, what the rotation in circular measure would be in each substance for the thallium ray between two points whose magnetic potentials differ by unity. See next page.

Relation between the Index of Refraction and the Magnetic Rotative Power.

In the same paper M. Becquerel has shown that for the same groups of substances the following relation approximately holds:—

$$\frac{R}{\mu^2(\mu^2-1)} = \text{const.}$$

where R is the magnetic rotative power and μ the index of refraction.

* T. lxxxvi. p. 1077.

† "Ann. de Chem. et de Phys., 1877, 5^{me} Serie," tom. xii. p. 5.

Table of Magnetic Rotative Powers.

Substance.	Specific gravity.	Index of Refraction.	Ratio of Rotation to that in Bisulphide of Carbon.	ω = Rotation in circular measure of the green thallium ray between two points whose magnetic potentials differ by unity.
		Yellow light.		
Bisulphide of carbon	1·263	1·6249	1·000	3·04763 × 10⁻⁵
Nitric Acid—fuming	...	1·4010	·206	·6278
" " ordinary	...	1·3740	·291	·8868
Sulphuric acid—monohydrate	1·854	1·4284	·247	·7527
" " SO_3 + 4 HO	...	1·4054	·286	·8716
Pure hydrochloric acid	1·1630	1·4071	·490	1·4933
Alcohol—methyl.	·836	1·3530	·253	·7710
" propyl.	·811	1·3836	·279	·8502
" butyl.	·807	1·3934	·294	·8960
" amyl.	·815	1·4046	·311	·9478
Chloroform	...	1·4520	·380	1·1581
Xylene	·866	1·4932	·525	1·6000
Toluene	·871	1·4928	·576	1·7554
Benzine	·883	1·4998	·636	1·9382
Silvine KCl (crystallized)	...	1·4830	·672	2·0480
Diamond (octohedral crystal)	...	2·4200	·301	·9173
Fluor Spar—1st specimen	...	1·4332	·207	·6308
2nd specimen	...		·234	·7131
Rock salt	2·260	1·5430	·843	2·5691
Glass—No. 1. Heavy flint	4·380	1·7200	1·360	4·1447
2. " "	4·860	1·7650	1·533	4·6720
6. Flint	3·168	1·5790	·771	2·3497
7. "	3·540	1·6140	·987	3·0080
8. Crown	2·559	1·5260	·481	1·4659
*Molten borate of lead (1)	...	1·7800	1·405	4·2819
" " " (2)	...		1·439	4·3855
Silicate of lead molten	...	1·8200	1·832	5·5832
Solution of sub-acetate of lead in water	...	1·3670	·375	1·1428
Protochloride of carbon	...	1·4580	·404	1·2312
Perchloride of carbon	...	1·5620	·761	2·3192
Cast borax	...	1·5010	·405	1·2343
Concentrated solution of nitrate of silver	...	1·4580	·424	1·2922
Chloride of silica	1·523	1·4090	·444	1·3531
Concentrated solution of nitrate of bismuth	...	1·4590	·452	1·3775

* "Fondu" may mean either "molten" or "cast."

TABLE OF MAGNETIC ROTATIVE POWERS (*continued*).

Substance.	Specific gravity.	Index of Refraction.	Ratio of Rotation to that in Bisulphide of Carbon.	ω = Rotation in circular measure of the green thallium ray between two points whose magnetic potentials differ by unity.
		Yellow light.		
Concentrated aqueous solution of potash	...	1·4230	·464	1·4141
Spinel coloured by chrome . . .	....	1·7150	·496	1·5116
Concentrated solution of chloride of magnesium	...	1·4300	·519	1·5817
Protochloride of phosphorus . .	1·450	1·508	·651	1·9840
Concentrated solution of perchloride of antimony	....	1·4600	·743	2·2643
Bichloride of sulphur, SCl	...	1·6190	·932	2·8403
Protochloride of sulphur, S_2Cl . .	1·687	1·6460	·984	2·9988
Chloride of arsenic	2·172	1·6006	1·000	3·0476
Bichloride of tin	2·200	1·5060	1·035	3·1542
Perchloride of antimony . . .	2·280	1·5910	1·656	5·0468
Bisulphide of hydrogen (impure) .	...	1·8850	1·743	5·3120
Molten sulphur at 114°	1·96	1·9290	1·904	5·8026
Sub-sulphide of phosphorus, Ph_2S .	1·8007	2·0661	2·592	7·8994
Molten phosphorus at 33°	1·77	2·0740	3·120	9·5086
Blende	4·095	2·3690	5·295	16·1372
Bichloride of titanium	....	1·6043	−·358	−1·0910
		Red light Li.		
Bromide of sulphur	2·696	1·7630	1·942	5·9184
Brome	2·970	1·616	1·960	5·9735
Chloride of selenium	2·589	1·8070	2·408	7·3387
Selenium	4·300	2·6558	10·960	33·4020
Oxyd de of copper	5·992	2·819	14·060	42·8496
Chlorochromic acid	...	...	−·080	−·2438
Distilled water	...	1·3340	·308	·9386 × 10^{-5}
Distilled water, direct observation (Gordon)	...	...	...	·4496 × 10^{-5}*

* There is a very large discrepancy here between M. Becquerel's result and my own. I cannot account for it.

The constant, however, has very different values for different groups of substances.

Rotation of Different Rays.

M. Becquerel has found that for the same substance the relation between the magnetic rotation of different rays is expressed very exactly by the formula—

$$\frac{R\,\lambda^2}{\mu^2\,(\mu^2-1)} = \text{const.}$$

where λ and μ are the wave lengths and refractive indices for the different rays respectively.

Now, for bisulphide of carbon we have—

Ray.	Wave length.*	Refractive Index.
D	5·892 .	1·6333†
E	5·269 .	1·6465†
Green Thallium .	5·349 .	1·6448‡

Hence we have that the rotation of any ray whatever in bisulphide of carbon, between two points whose magnetic potentials differ by unity, will be in circular measure.

$$\omega = \frac{(1·6448)^2\{(1·6448)^2-1\}\,(3·04763\times 10^{-5})}{(5·349\times 10^{-5})^2}\cdot\frac{\lambda^2}{\mu^2(\mu^2-1)}$$

$$= 5·9966\times 10^4\,.\,\frac{\lambda^2}{\mu^2(\mu^2-1)}.$$

Rotation in Vapour.

In the *Philosophical Magazine* for March, 1879, Professors A. Kündt and W. C. Röntgen publish an account of some experiments in which they have succeeded in obtaining a magnetic rotation of the plane of polarization of light in the saturated vapour of bisulphide of carbon at a temperature of 100° C. They first used a column of vapour rather more than 1 metre long, then one of 2·4 metres. A set of helices, containing 2400 turns of wire, and a battery of sixty-five Bunsen cells

* Watt's "Index of Spectra."

† Everett, "Units and Physical Constants," p. 72.

‡ By interpolation.

were employed. They obtained a distinct rotation, which they estimate at about $\frac{1}{2}°$. At the time when this paper was written they had not as yet succeeded in obtaining any effect with air, but had seen a rotation in gaseous sulphurous acid at 100° C., and a pressure of twenty atmospheres, and in sulphuretted hydrogen gas at a pressure of twenty atmospheres and ordinary temperature.

Rotation in Gases.

On March 31, 1879, M. Henri Becquerel* announced that he had measured the amount of rotation obtained with various gases. The apparatus consisted of a copper tube, three metres long, containing the gas and surrounded by six helices each half a metre long, and each containing about 15 kilos. of copper wire three millims. in diameter.

The light of a lime-light was used, and by means of reflectors it was caused to travel nine times along the tube,† so that it passed through 27 metres of gas.

With coal gas and yellow light, a double rotation of $+ 6'{\cdot}8$ was observed. With the same magnetic force, under the same conditions, bisulphide of carbon gave a rotation of $+ 513°$ or $30{,}780'$. The ratio of the rotation of coal gas to that of bisulphide is about

$$+ \cdot 00022$$

On multiplying my value of Verdet's constant by this ratio, we find that between two points in coal gas, whose magnetic potentials differ by unity in C.G.S. measure, the green light of thallium would have its plane of polarization twisted

$$6 \times 10^{-9}$$

of a unit of circular measure.‡

Some experiments on oxygen showed that its "magnetic rotative power" is negative, or opposite to that of bisulphide of carbon and of coal gas.

* "Comptes Rendus," tom. lxxxviii. p. 709.

† See vol. ii. p. 207, fig. 239.

‡ The calculation comes out $6{\cdot}732 \times 10^{-9}$, but M. Becquerel informs me that he does not consider his result trustworthy to more than the first figure.

Rotation in Gases—Kündt and Röntgen's Experiments.

On May 13, 1879, a paper by Messrs. Kündt and Röntgen was read before the Munich Academy,* in which the authors announce that they have succeeded in measuring the magnetic rotative powers of various gases.

The gases were examined at a pressure of 250 atmospheres.

They were contained in a copper tube 1·5 metres long, three millims. internal and ten millims. external diameter. The glass ends of the tube were kept in position by a steel screw press at each end. This arrangement was so successful that when the tube was filled with gas at a pressure of 250 atmospheres, no appreciable loss occurred even in twelve hours.

It was found that the pressure so strained the glass ends that they became doubly refracting. For this reason plates of tourmaline were used as the polarizer and analyzer, and were placed in the tube *inside* its ends.

One was fixed to the end which was clamped, and the other was rotated by turning the whole tube with the exception of the end to which the analyzing tourmaline was fixed.

Six large helices, connected as one, were placed outside the tube.

The current was measured by leading it through a small helix, surrounding a short tube containing bisulphide of carbon, and observing the rotation.

The actions of the two helices were compared by removing the gas tube and placing in the large helix a long tube containing bisulphide of carbon.

The amount of rotation was measured by a mirror and telescope.

The compression was commenced by means of an ordinary pump, and completed by forcing glycerine by means of a hydraulic press into a large iron reservoir connected to the gas tube.

As no manometer would accurately measure these high pressures, they were computed by a comparison of the volume of the tube with the volume occupied by a known fraction of the compressed gas after expansion.

* "Ueber die electro-magnetische Drehung der Polarizationsebene des Lichtes in dem Gasen," von A. Kundt und W. C. Röntgen. Sitzungsber. zu München, 1879, ii. "Math. Phys.," p. 148.

It was found that the gas was opaque for several hours after being compressed. This was caused by the fact that the gas was heated by compression, heated the sides of the tube, and caused unequal refractions. To hasten the cooling, the tube was surrounded by a jacket through which flowed a stream of cold water.

RESULTS.

It was found that—

(1) *Atmospheric air, oxygen,* nitrogen, carbonic oxide, carbonic acid, coal gas, ethyl, and marsh gas, all turn the plane of polarization in the direction of the magnetizing current—that is, that their rotation is in the same direction as that of water and bisulphide of carbon.*

(2) *That the amount of rotation, under the same circumstances, varies greatly in different gases.*

(3) *That in any gas, under similar circumstances, the rotation is proportional to the density.*

The following is a general table of the results:—

Gas.	Pressures used. in different experiments with different current strengths. Atmospheres.	Rotations measured.	d = number of atmospheres by which the gas would have to be compressed to make it act as powerfully as liquid bisulphide of carbon.	$S = \frac{1}{d}$ = ratio of rotation in the gas at 760mm.&0°C to that in liquid bisulphide of carbon.	ω = rotation in circular measure of the green thallium ray between two points whose magnetic potentials differ by unity in the gas at 0° C.& 760 mm.
Hydrogen	121 to 210	51′ to 1° 41′	7253	·0001379	$4{\cdot}20268 \times 10^{-9}$
Oxygen	70 to 237	38′ to 2° 5′	6782	·0001474	$4{\cdot}49220 \times 10^{-9}$
Air	144 to 227	55′ to 1° 53′	5195	·0001819	$5{\cdot}54364 \times 10^{-9}$
Carbonic Oxide	172 to 222	1° 51′ to 3° 3′	3862	·0002589	$7{\cdot}89031 \times 10^{-9}$
Marsh gas	113 to 190	2° 32′ to 5° 15′	2481	·0004031	$12{\cdot}28499 \times 10^{-9}$

* We see that this result does not agree with M. Becquerel's.

Professor Röntgen, in a letter dated April 28, 1880, has sent me the results (not yet published) of a further investigation of the same subject by himself and Prof. Kündt.

They have compared the action of the gases with the action of a tube of water of equal length. The water tube was compared with bisulphide of carbon. They found the following numbers. S and ω have the same meanings as in the above table.

	Oxygen.	Nitrogen.	Air.	Hydrogen.	Carbonic Oxide.
S	·000109	·000127	·000127	·000132	·000232
ω	$3{\cdot}322 \times 10^{-9}$	$3{\cdot}870 \times 10^{-9}$	$3{\cdot}870 \times 10^{-9}$	$4{\cdot}023 \times 10^{-9}$	$7{\cdot}060 \times 10^{-9}$

Effect of Earth's Magnetism.

From a comparison of their results with those of myself and of M. Becquerel, Messrs. Kündt and Röntgen calculate what would be the rotation produced in atmospheric air by the action of the earth's magnetism.

They find that light travelling in a north and south direction would have to pass through 253 kilometres, or 158 miles, to be rotated 1°.

Rotation in Air caused by Earth's Magnetism—Becquerel.

On Nov. 17, 1879, M. Henri Becquerel announced to the French Academy* that he had succeeded in observing a rotation caused by the action of the earth's magnetism on the atmosphere.

It is known that the light of the sky is polarized in a plane, sensibly coinciding with one passing through the sun, the observer, and the point of the sky observed, and we will in future call this plane the "plane of the sun."

M. Becquerel first discusses the fact which he has discovered, that this coincidence is not exact; he then goes on to show that, if no disturbing cause interfered, the plane of polarization and the plane of the sun would coincide when the sun is vertical.

It is found, however, that there is a small angle between the planes, and this angle is caused by the action of the earth's magnetism on the air.

* "Comptes Rendus," tom. lxxxix. p. 838.

The following determinations were made:—

Points looked at.	Apparent zenith distance.	Observed rotation.	Maximum probable error.
Point on the Southern horizon	85°·0′	0°·22′	± 5′
Point on the Northern horizon	86° 26′	0°·24′	± 5′
Point on the South magnetic meridian	85°·20′	0°·42′	± 12′
	87°·27′	0°·59′	± 15′

No rotation could be observed in a region perpendicular to the compass needle.

THEORY.

The explanation of the phenomena of magnetic rotation of polarized light is still exceedingly obscure; and it is not likely that any complete explanation can be offered until we know a great deal more of the nature both of magnetism and light than we do at present. Prof. Maxwell * has given a provisional explanation which is based on the following reasoning:—

We know that two uniform circular vibrations of the same amplitude, having the same periodic time, and in the same plane, but revolving in opposite directions, are equivalent to a rectilinear vibration whose direction passes through the points where two particles describing the given circular paths in the given manner would pass each other.

We also know that if we accelerate either vibration, we turn the direction of the equivalent rectilinear vibration in the direction of the added motion.† This acceleration may be produced by a motion of the medium in which the vibrations take place.

Such motion, which must be rotatory, may be either a motion of the medium or of sensible portions of it as a whole, or it may be motions of the molecules of the medium.

* "Electricity," 811, vol. ii. p. 402.

† I have not given any explanation of the theory of the composition of vibrations, as it would be out of place in a work on Electricity. There is an very clear explanation of it in Mr. Spottiswoode's work on Polarization, before mentioned. To this the student is referred, as it is impossible to understand the relations between electricity and light without a previous knowledge of the elementary phenomena of polarization.

Common experience shows us that there is no motion of sensible portions of the medium; any rotatory motion, then, which exists must be rotations of the molecules on their own axes. Such motions, though not able to produce an effect on any substance perceptible by ordinary methods, may possibly be rendered sensible by the delicacy of the mode of investigation afforded us by the use of polarized light.

The theory which ascribes magnetic and other effects to the rotatory motion of the molecules is called "the theory of molecular vortices."—For an account of it the reader is referred to Maxwell's "Electricity" (arts. 822-831), vol. ii. pp. 408-417—the theory being far too complex and too purely mathematical to be discussed in this work. Here, however, are two quotations from Prof. Maxwell which I may fairly introduce :—

"We have been hitherto obliged to use language which is perhaps too suggestive of the ordinary hypothesis of motion in the undulatory theory. It is easy, however, to state our result in a form free from this hypothesis.

"Whatever light is, at each point of space there is something going on, whether displacement, or rotation, or something not yet imagined, but which is certainly of the nature of a 'vector' or directed quantity, the direction of which is normal to the direction of the ray. This is completely proved by the phenomena of interference.

"In the case of circularly-polarized light, the magnitude of this vector remains always the same, but its direction rotates round the direction of the ray, so as to complete a revolution in the periodic time of the wave.

"The uncertainty which exists as to whether this vector is in the plane of polarization or perpendicular to it, does not extend to our knowledge of the direction in which it rotates in right-handed or in left-handed circularly-polarized light respectively. The direction and the angular velocity of this vector are perfectly known, though the physical nature of the vector and its absolute direction at a given instant are uncertain.

"When a ray of circularly-polarized light falls on a medium under the action of magnetic force, its propagation within the medium is affected by the relation of the direction of rotation of the light to the direction of the magnetic force. From this we

conclude, by the reasoning of Art. 820 [Maxwell's 'Electricity'] that in the medium, when under the action of magnetic force, some rotatory motion is going on, the axis of rotation being in the direction of the magnetic forces; and that the rate of propagation of circularly-polarized light, when the direction of its vibratory rotation and the direction of the magnetic rotation of the medium are the same, is different from the rate of propagation when these directions are opposite.

"The only resemblance which we can trace between a medium through which circularly-polarized light is propagated, and a medium through which lines of magnetic force pass, is that in both there is a motion of rotation about an axis. But here the resemblance stops, for the rotation in the optical phenomenon is that of the vector which represents the disturbance.

"This vector is always perpendicular to the direction of the ray, and rotates about it a known number of times in a second. In the magnetic phenomenon, that which rotates has no properties by which its sides can be distinguished, so that we cannot determine how many times it rotates in a second.

"There is nothing, therefore, in the magnetic phenomenon which corresponds to the wave-length and the wave-propagation in the optical phenomenon. A medium in which a constant magnetic force is acting is not, in consequence of that force, filled with waves travelling in one direction, as when light is propagated through it. The only resemblance between the optical and the magnetic phenomenon is that, at each point of the medium, something exists of the nature of an angular velocity about an axis in the direction of the magnetic force." *

The second quotation follows a mathematical discussion of the theory of molecular vortices.

"I think we have good evidence for the opinion that some phenomenon of rotation is going on in the magnetic field; that this rotation is performed by a great number of very small portions of matter, each rotating on its own axis, this axis being parallel to the direction of the magnetic force, and that the rotations of these different vortices are made to depend on one another by means of some kind of mechanism connecting them.

"The attempt which I have made to imagine a working model of this mechanism must be taken for no more than it really is—

* "Electricity," 821, vol. ii. p. 407.

a demonstration that mechanism may be imagined capable of producing a connection mechanically equivalent to the actual connection of the parts of the electro-magnetic field. The problem of determining the mechanism required to establish a given species of connection between the motions of the parts of a system always admits of an infinite number of solutions.

"Of these, some may be more clumsy or more complex than others, but all must satisfy the conditions of mechanism in general. The following results of the theory, however, are of higher value:—

"(1) Magnetic force is the effect of the centrifugal force of the vortices.

"(2) Electro-magnetic induction of currents is the effect of the forces called into play when the velocity of the vortices is changing.

"(3) Electro-motive force arises from the stress on the connecting mechanism.

"(4) Electric displacement arises from the elastic yielding of the connecting mechanism." *

* "Electricity," 831, vol. ii. p. 416.

CHAPTER XLVII.

DR. KERR'S DISCOVERIES.

RELATION BETWEEN STATICAL ELECTRICITY AND POLARIZED LIGHT.

IN the Phil. Mag. for Nov. 1875, Dr. Kerr, of Glasgow, announced a very remarkable discovery.

He finds that when glass and certain other dielectrics are subjected to an intense electric strain, they acquire the power of double refraction, and hence convert plane into elliptically polarized light.

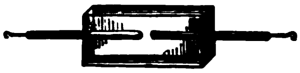
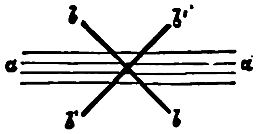


Fig. 248.

In his first experiments a piece of thick plate-glass (fig. 248) had two holes drilled from its edges parallel to its faces, to within ¼ inch of one another. Wires inserted in these were connected to an induction coil, and light polarized in a plane at 45° (fig. 249) to



a a line of electric strain.
b b, *b b'* direction of optical vibrations.
Ray of light perpendicular to plane of paper.

Fig. 249.

the line of the wires passed perpendicularly through the glass, and was received in a second Nicol placed so as to extinguish it.

When the coil is worked, sparks pass in the air between the ordinary discharging rods, and the glass is subjected to a stress which increases as the discharging points are drawn further apart.

As soon as the points are far enough apart for the stress to be considerable, the light reappears and cannot be extinguished by any rotation of the Nicol.

If the angle between the plane of polarization and the line of electric stress differs from 45°, the effect diminishes and it becomes zero when the angle is 0° or 90°.

In a second paper,* Dr. Kerr announces that he has succeeded in obtaining the effect with the following liquids:—

Bisulphide of carbon, benzol, paraffin, and kerosene oils, oil of turpentine and olive oil.

Since Dr. Kerr's discovery was first announced, I have, by the use of larger apparatus (fig. 250) than that which then was at

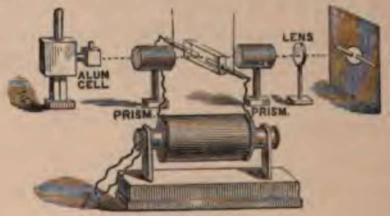


Fig. 250.

Dr. Kerr's disposal, succeeded in so magnifying the effect as to enable me to project it on a screen by the electric light, so that it was clearly seen by a large audience at the Royal Institution on Feb. 6, 1879.

The images of the points were about $1\frac{1}{2}$ inches apart, and a patch of white light about 3 inches across appeared on the screen when the coil was worked.†

* Phil. Mag., Dec. 1875, p. 446.

† When rehearsing the experiment the day before the lecture, the electro-static stress was accidentally allowed to become strong enough to perforate the glass. Immediately before perforation there occurred some very remarkable effects.

First appeared a patch of orange-brown light about 6 or 7 inches diameter This at once resolved itself into a series of four or five irregular concentric rings, dark and orange-brown, the outer one being perhaps 14 inches in diameter. In about two seconds more these vanished and were succeeded by a huge black cross about 3 feet across, seen on a faintly luminous ground. The arms

In the Phil. Mag. for August and September, 1879, Dr. Kerr describes a later and more extended series of experiments on the same subject. All the dielectrics were liquids, and were contained in a specially constructed cell; and the electricity was obtained from a common plate machine. Dr. Kerr concludes his papers with the following summary of results:—

"(1) When an insulating liquid is traversed by electrostatic force, it exerts a purely birefringent action upon transmitted light. In relation to this action, liquids are divisible into two classes, the positive and the negative.

"(2) Positive liquids act as glass extended in a direction parallel to the lines of electric force, or as plates of quartz or other positive uniaxals with axes parallel to the lines of force. Bisulphide of carbon is the best example.

"(3) Negative liquids act as glass compressed in a direction parallel to the lines of force, or as plates of Iceland spar or other negative uniaxals with axes parallel to the lines of force. Oil of colza is one of the best examples.

"(4) In the following table the positive liquids are arranged as nearly as possible in the descending order of electro-optic power, the larger and clearer intervals being marked by separating lines. The negative liquids are not so arranged; but colza and seal oils are certainly among the strongest, and linseed is the weakest.

---

of the cross were along the planes of polarization, and therefore (the experiment being arranged according to Dr. Kerr's directions) were at 45° to the line of stress.

The glass then gave way, and all the phenomena disappeared except the extreme ends of the cross; and the discharge through the hole, where the glass had been perforated, was alone seen.

The phenomena was seen by Mr. Cottrell, by Mr. Valter (the second assistant), and by myself. A fresh glass plate was at once drilled, in hopes of repeating the experiment in the lecture next day, but, owing to sparks springing round, we did not succeed in perforating the glass, and therefore saw only the faint return of light described by Dr. Kerr.

I have since made a great many more experiments, and have destroyed a good many expensive glasses, but in every case perforation has occurred suddenly, instead of gradually, and therefore I have never succeeded in reproducing the effects. Proc. Roy. Soc., Feb. 13, 1879. Compare vol. ii. p. 253.

Positive Liquids.	Negative Liquids.
Bisulphide of carbon.	Fixed oils of vegetable origin:—
———	Colza,
Cumol.	Sweet almonds,
Paraffin oil (sp. gr. ·890).	Olive,
———	Poppy-seed,
Carbon dichloride.	Rape-seed,
Xylol.	Nut,
Toluol.	Mustard-seed,
Cymol.	Linseed.
Benzol.	Fixed oils of animal origin:—
———	Seal,
Amylene.	Codliver,
———	Lard,
Paraffin-oil (sp. gr. ·814.	Neatsfoot.
Sperm-oil.	
Terebene.	
Bromtoluol.	
———	
Valeric acid?	

"The birefringent actions of these twenty-six dielectrics have been observed repeatedly; they are perfectly regular, and, to sense, perfectly pure. Valeric acid alone is so faint as to be doubtful.

"(5) All the negative liquids yet known belong to the class of the fixed oils. Sperm-oil holds an exceptional place, being clearly positive.

"(6) The influence of density on electro-optic power is marked and certain in the case of the paraffin oils, increase of density being accompanied by increase of electro-optic power.

"(7) In bisulphide of carbon and several other liquids, electro-optic measurements are manageable through long ranges of potential and optical effect.

"(8) Stannic chloride exerts a very strong optical action under electrostatic force; but the character of the effect is not yet certainly known.

"(9) Of the forty or more liquids yet examined in the plate cell, there are none that exhibit any moderate degree of insulating power except the twenty-seven now named in (4), (8). This appears to justify the generality of the statement made in (1).

"(10) When nitrobenzol is traversed by an intense electric current, it exerts a purely birefringent action on transmitted light. The action is similar to that of a positive uniaxal plate with axis parallel to the line of discharge."

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Plate LII.—Röntgen's Repetition of Kerr's Electro-Optic Experiments.

Vincent Brooks, Day & Son, Lith.

PROF. RÖNTGEN'S EXPERIMENTS.—PLATE LII.

On December 31, 1879, Prof. W. C. Röntgen of Geissen gave an account * of a repetition of Dr. Kerr's experiments which he has made on a large scale.

Prof. Röntgen used large Nicols, a powerful lime-light, and a glass cell twelve centims. high, six wide, and three thick, filled with bisulphide of carbon. The electrodes were so arranged that the lines of force were vertical.

Magnificent effects were observed. When the electric machine was worked, the light returned so intensely that the eye could not bear to look at it.

These beautiful effects were obtained, not only when the planes of the crossed Nicols were at 45° to the vertical, but when they were parallel and perpendicular to it.

This at first sight appears not to agree with what Dr. Kerr has stated, namely, that there is no restitution when the planes are parallel or perpendicular to the lines of force, and a maximum when they are at 45° to them.

An examination of Plate LII. will, however, show us that this discrepancy is only apparent.

Figs. 1, 3, 5, show the effects obtained with different electrodes when the planes of the crossed Nicols were at 45° to the vertical—called "Position I." of the Nicols.

Figs. 2, 4, 6, show the corresponding effects when the planes were vertical and horizontal—called "Position II." of the Nicols.

Fig. 1.—The electrodes consisted of a brass plate at the bottom of the cell, connected to earth, and a brass ball one centim. in diameter above it, connected to the electrical machine.

We see that the greater portion of the field is illuminated, the middle most brightly. There are, however, two dark "tails" (Schwänze) which curve downwards from the sides of the ball.

The directions of these tails pass through the centre of the ball, and leave its surface at angles of $\pm$ 45° with the vertical.

When the liquid in the cell is not quite clean, the dust particles arrange themselves along the lines of force and allow the direction of the latter to be seen. The lines of force are

* "Ueber die von Herrn Kerr gefundene neue Beziehung zwischen Licht und Elektricitat," xix. Ber. d. Oberh. Gesellsch. f. Natur- u. Heilk, p. 1.

vertical at the centre of the field; but as they start from each portion of the ball at right angles to its surface,* and curve round to the plate, they must be in all directions at different parts near the edge of the field.

The dark tails are the "locus" of points where the tangent to the lines of force is parallel or perpendicular to the plane of polarization.

Fig. 2 is complementary to fig. 1. The lines of force and the plane of polarization are parallel or perpendicular to each other at the centre of the field, and consequently there is a vertical dark line; at the sides they are at 45°, and therefore those regions are brightly illuminated.

In Dr. Kerr's experiments a small field only was used, and, consequently, when the planes of his Nicols were vertical and horizontal, he saw no light, because he was looking at the region occupied by the vertical dark band in fig. 2.

Thus Prof. Röntgen's experiments entirely confirm Dr. Kerr's discovery, that the electricity exercises its maximum effect on the light when the line of force and the plane of polarization make an angle of 45°, and that there is no effect whatever when they coincide or are at right angles.

Effect of Strained Glass Compensator.

When glass is so strained as to make it act like a crystal of opposite sign to the dielectric, it produces reversed effects, or, if used with the dielectric, it more or less compensates the electro-optic effect according to the amount of strain.

When a piece of glass is inserted in the beam of light producing fig. 1, and is compressed vertically, the tails gradually go together and finally join, and form one band similar to that in fig. 2. If the compression is still further continued, the tail is apparently drawn up to the ball, and at last disappears.

When the glass is compressed horizontally, the reverse appearance is produced, the middle of the field becomes brighter, and the sides darker, and the tails bend outward.

When the Nicols are in Position II., no effect is produced by compressing the compensator in a vertical or horizontal direction.

* For the surface of a conductor is an equipotential surface, and the lines of force are perpendicular to it. Vol. i. pp. 29, 30.

When it is placed at an angle of 45°, it causes the field to become unsymmetrical.

Figs. 3 and 4.—The lower electrode consists of a ball one centim. diameter, the upper of a stout brass wire.

Fig. 3 and 4 represent respectively the effects observed with the Nicols in Positions I. and II.

The dark tails in both cases trace out the "locus" of points where the lines of force are parallel and perpendicular to the planes of polarization.

Figs. 5 and 6 are the corresponding pair of appearances seen with electrodes, consisting of stout rectangular brass rods. The dark brushes are again the same "locus."

Various other electrodes were tried with similar results.

Other Dielectrics.

The effect was also obtained with cod-liver oil. It acted more feebly than bisulphide, and in the opposite direction. Bisulphide of carbon acted like glass *extended* along the lines of force, cod-liver oil like glass *compressed* in the same direction.

Thus the classification of fluids into positive and negative, similar to positive and negative crystals, is completely established. Turpentine acted like cod-liver oil.

Experiments on partially-conducting Liquids.

The effects were obtained with nitro-benzol, sulphuric ether, glycerine, and distilled water, but only when an air-spark was interposed in one of the wires, and the machine connected to a Leyden jar.

A flash of light was then seen in the field corresponding to each spark. This result is especially interesting as showing that there is a momentary state of strain in conductors before it is relieved by the yielding of the material.

Exhausted Tube.

Prof. Röntgen tried passing the light across a vacuum tube which was so highly exhausted that no discharge could pass. No effect was observed even when a very strong difference of potential was maintained at the terminals.

Moving Liquid.

Prof. Röntgen found that he was able to partially imitate the

optical effects of electric strain by driving the fluid in a strong stream through the cell.

Different Dielectrics.

In comparing different liquids, Prof. Röntgen found, agreeably to Dr. Kerr's more extended results, that dielectrics under electric strain act on light like uniaxal crystals with the line of electric strain for axis, and that, like crystals, they vary from strong to weak, and from positive to negative.* Bisulphide of carbon acts as a positive crystal.

Dr. Kerr's Electro-optic Law.

In March, 1880,† Dr. Kerr published the results of a series of quantitative measurements of the electro-optic effect. His experiments were all made on bisulphide of carbon, but there seems but little doubt that the law established by experiments on it is of general and universal application.

The following law was found to hold with absolute accuracy:—

The intensity of electro-optic action of a given dielectric—that is, the quantity of optical effect (or the difference of retardations of the ordinary and extraordinary rays) per unit of thickness of the dielectric—varies directly as the square of the resultant electric force.

Instruments—The Cell.

The cell (fig. 251) consisted of a block of plate glass ten inches by six inches, built up of three slabs placed vertically, and having a joint thickness of exactly $3\frac{1}{1}\frac{5}{6}$ inches.

Fig. 251 shows an end view of the block. The inner rectangle represents a tunnel passing right through it. The ends of the tunnel are closed by panes of thin, clear plate glass. Outside the panes are pieces of thick india-rubber cloth, and outside the cloths are stout mahogany planks, longer than the ends of the cell, and connected together by stout screw bolts at each end. There are holes in the planks and cloths, somewhat larger than the ends of the tunnel.

* All uniaxal crystals divide the ray of light into two—the "ordinary" and "extraordinary." Whichever ray travels slowest is most refracted. Crystals in which the ordinary ray goes fastest are called positive; those in which the extraordinary ray goes fastest are called negative. See Spottiswoode, "Polarization of Light," p. 92.

† Phil. Mag., 1880, i. p. 157.

By tightening the screw bolts, the cell could be perfectly closed without the use of any cement whatever.

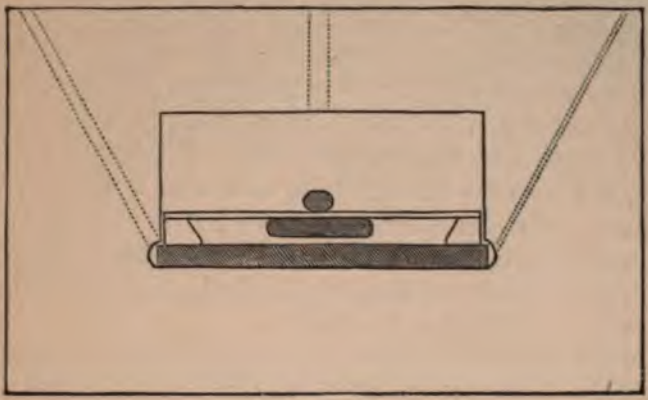


Fig. 251.

The shaded pieces represent the conductors. The lower one is a wide, thick brass plate resting on the floor of the cell; the upper is a narrower plate supported from glass rafters, to which it is attached by bullet-headed screws. Both plates are the full length of the tunnel, viz. $3\frac{15}{16}$ inches.

The dotted lines in fig. 251 represent three borings. The connecting wires to the upper and lower plates pass respectively through the vertical boring, and through the narrow one on the right.

The larger boring on the left is used to fill and empty the cell.

Chromatic Effects.

In the preliminary work with this cell, some very fine chromatic effects were observed.

The following is Dr. Kerr's account of them :—

"Here, as in all the following experiments, the cell is charged with rather less than a pint of clean bisulphide of carbon. No other optical pieces are employed at present than the charged cell and a couple of Nicol's prisms.

"A beam of light from a bright cloud is reflected horizontally into the room through an opening in the window-shutter, passes through the first Nicol, then perpendicularly through the plate of liquid, then through the ocular Nicol. The pieces are so levelled and directed that the observer at the polariscope looks

fairly through the deep slit that separates the two conductors in the cell. I may mention again that the dimensions of the slit are about *one-twelfth* of an inch, *one* inch, and *four* inches—the first dimension lying vertically as the lines of force, and the last lying horizontally along the line of sight. The two Nicols are fixed, the first with its principal section at 45° to the vertical, and the second at extinction, which is here quite pure. Wires are led permanently from the two conductors—from the lower to earth, and from the external knob of the upper to the prime conductor. To give greater steadiness and distinctness to the progress of the optical effect, the wire from prime conductor to cell is put in permanent contact with the knob of a Leyden jar, whose outer coating is uninsulated.

"When the machine is set in motion at a moderate rate, the potential of the upper conductor rises slowly, and the black space between the two conductors is illuminated, the light passing gradually through impure black, faintly bluish grey, faint white, and so forward, up to a sensibly pure and brilliant white. Thus far there is nothing new, except that the highest potential yet reached is comparatively low, while the optical effect is very large, and already far beyond neutralization by the action of any hand compensator of strained glass.

"As the potential of the prime conductor still rises, the polariscope gives a fine progression of chromatic effects, which descend regularly and continuously through a certain range of Newton's scale. The luminous band between the conductors passes first from white to a bright straw-colour, which deepens gradually to a rich yellow, then passes through orange to a deep brown, then to a pure and dense red, then to purple and very deep violet, then to a rich and full blue, then to green. All the colours are beautifully dense and pure, certainly as fine as any that I have ever seen in experiments with crystals in the polariscope.

"Generally about the point last named of the scale of colours, at or near the green of the second order, the process terminates in spark-discharge through the liquid. Sometimes, but not frequently in my observations, it terminates at an earlier stage, to run its regular course at the next trial. The irregularity appears to be due to an accidental precipitation of discharge by the action of solid particles, impurities in the liquid.

"Through this whole range of effect, from the pale blue or impure black of the first order to the green of the second order, the plate of electrically-charged liquid acts regularly as a uniaxal crystal, as a plate of quartz with optic axis parallel to the lines of force, the plate increasing in thickness continuously and very rapidly as the potential rises."

INSTRUMENTS CONTINUED—ELECTROMETER.

To measure potential, a Thomson long-range electrometer was used.

This is a modification of the absolute electrometer described in vol. i. page 55.*

THE JAMIN COMPENSATOR.†

To measure the optical effect, a Jamin compensator was used.

This consists of two crystals of quartz (fig. 252), cut into

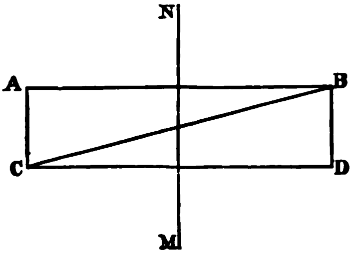


Fig. 252.

two prisms, ABC, DCB. The light passes through in the direction MN. The axis of one of the crystals is in the plane of the paper, that of the other is at right angles to it.

One of the prisms is fixed in a tube. The other can be moved by means of a micrometer screw.

Black bands are seen in the field of view. By turning the screw the retardation is altered, and the black bands move.

A fine silk thread is stretched across the field of view.

We adjust one band on the thread, and note on the scale of the micrometer what number of divisions it is necessary to move the micrometer screw to bring the next band to the thread.

The difference of retardation corresponding to the difference of distance between two bands can be calculated mathematically,

* See Thomson, "Electro-statics and Magnetism," § 383, p. 306.

† Jamin, "Cours de Physique," tom. iii. pp. 622, 639.

and we can thus calculate the amount of retardation corresponding to one scale division.

The compensator is placed in the path of the ray which has passed through the electro-optic cell, and adjusted so that a black band lies on the thread. On the machine being worked, the band is displaced.

The compensator screw is then turned till the band returns to its original position. The number of scale divisions through which it is moved give the retardation caused by the electric strain.

Simultaneous observations of the electrometer and compensator give the retardation caused by different differences of potential. The general arrangement of the apparatus is as in fig. 253.

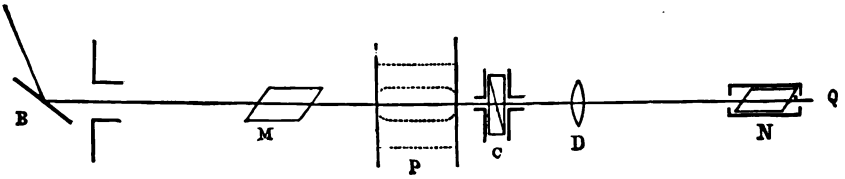


Fig. 253.

B is a mirror which reflects the light into the apparatus, M N are the Nicols, P the cell, C the compensator, D a lens, and Q the position of the observer's eye.

CALCULATION.

Let V be the difference of potentials as measured by the electrometer, D the distance between the plates, R the resultant electric force, Q the quantity of optical effect.

We then know that for a small field, and for portions of it not near its edges, R is proportional to V and inversely proportional to D, and we may write,

$$R = \frac{V}{D}.$$

But we have stated that

Q is proportional to R^2,

or

$$Q \propto R^2 \propto \frac{V^2}{D^2}* \quad . \; . \; . \; . \; . \; . \; (1)$$

* The sign $\propto$ means "is proportional to."

If the values of Q are calculated by this formula, the agreement or disagreement of the results with the observed values of Q will be a test of the accuracy of the law stated on page 252.

The following results were obtained for different potentials, and with different distances between the plates :—

D measured . .	1	2	2	3	3	4	4
V measured . .	60	90	120	90	120	120	150
Q measured . .	63	36	64	16	27	15	24
Q calculated . .	63·1	35·5	63·1	15·8	28	15·8	24·6

Further comment is superfluous. "Kerr's Electro-optic Law" is entirely established.*

Dr. Kerr concludes his paper as follows :—

"In conclusion, I observe that the principal result of the experiments, what I have called the Law of Squares, may be correctly stated in several very different forms. The quantity of optical effect, per unit of thickness of the dielectric, varies either—

"(1) Directly as the square of the resultant electric force, or

"(2) Directly as the energy of the electric field per unit of volume, or

"(3) Directly as the mutual attraction of the two conductors that limit the field, or

"(4) Directly as the *electric tension* of the dielectric, a quantity that was conceived long ago very clearly by Faraday, and introduced afterwards definitely into the Mathematical Theory of Electricity by Professor Clerk Maxwell.

"Faraday's and Clerk Maxwell's views as to the action of the dielectric in the transmission of electro-static force, and as to the state of molecular constraint that is associated with and essential to that action, are very strongly confirmed by the new facts of electro-optics. The dioptric action of an electrically-charged medium is closely related to the electric stress of the medium, the axis of double refraction coinciding in every case with the line of electric tension, and the intensity of double

* An experiment is given to show that the effects are unaltered when the sign of V is changed and its numerical value remains constant.

refraction varying, certainly in bisulphide of carbon and probably in all other dielectrics, directly and simply as the intensity of the tension."

We cannot imagine a more complete proof than Dr. Kerr's experiments afford that electric induction is a "state of strain" in the dielectric.

CHAPTER XLVIII.

Dr. Kerr's Discoveries (*continued*).

ROTATION OF THE PLANE OF POLARIZATION OF LIGHT REFLECTED FROM THE POLE OF A MAGNET.

Dr. Kerr has also made another most remarkable discovery.* He finds that—

"When plane-polarized light is reflected regularly from either pole of an electro-magnet of iron, the plane of polarization is turned through a sensible angle in a direction contrary to the nominal direction of the magnetizing current—so that the true south pole [the north-pointing pole] of polished iron, acting as a reflector, turns the plane of polarization right-handedly."

The experimental arrangements were as follows:—

L (fig. 254) is the source of light.

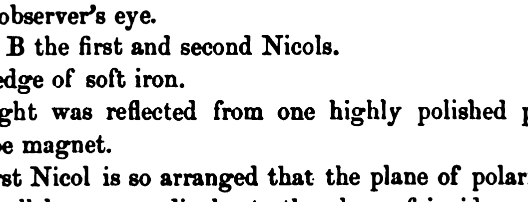


Fig. 254.

E the observer's eye.

A and B the first and second Nicols.

C a wedge of soft iron.

The light was reflected from one highly polished pole of a horse-shoe magnet.

The first Nicol is so arranged that the plane of polarization is either parallel or perpendicular to the plane of incidence, because

* Phil. Mag. May, 1877.

in any other case the light becomes elliptically polarized by reflection.

It has always been found necessary to employ, what Dr. Kerr calls, a "sub-magnet," namely, a wedge (C) of soft iron kept by slips of wood at a distance of about $\frac{1}{25}$ inch from the iron surface, so that there is just room for the light to pass. Dr. Kerr believes that the only action of a sub-magnet is to cause a greater concentration of magnetic force on the iron mirror. This point, however, requires further investigation.

In all cases of oblique incidence it was found that the effect on the polariscope was mixed, being partly due to the magnetic force, and partly to metallic reflection. The effect of the latter was to convert the plane-polarized light into light more or less elliptically polarized, and which was therefore not extinguishable by any rotation of the second Nicol.

To obtain the pure magnetic effect, Dr. Kerr arranged for the incidence of the light to be normal to the mirror as shown in fig. 255. The sub-magnet C was perforated and the light was re-

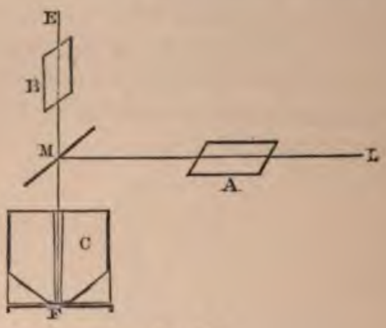


Fig. 255.

flected down on to the polished pole F by means of an unsilvered glass mirror M, through which the reflected light passes through the second Nicol to E.

With this arrangement the rotation due to the magnetic force is seen alone, and is quite distinct. The magnet used consisted of an iron core, two inches diameter and ten inches long, surrounded by about 400 turns of wire. It was worked by six small Grove's cells. The rotations were very small.

Nothing, however, could be more conclusive than Dr. Kerr's

paper. In it every possible doubt which could be cast upon the reality of the phenomenon seems already answered.*

Enough is not yet known about the laws of the new phenomena to enable us to discuss their theory.

Repetition of the Experiments.

The present writer has repeated Dr. Kerr's experiments, using an iron cylinder, 2 feet 4 inches long, and 2½ inches diameter, on which were placed the two helices belonging to the electro-magnet described in vol. ii. page 13.

The Jellett analyzer (vol. ii. p. 229) was used to measure the rotation.

The following readings of the plane of polarization were taken:—

Current direct.	Current reversed.
271° 55′	271° 30′
271 57	271 27
271 54	271 28
271 52	271 26
Mean double rotation .	. 26′ 45″

I have not as yet been able to get any distinct effect without the sub-magnet. Until this can be done, "absolute" measures of the amount of rotation due to a given strength of pole will not be possible.

Light Reflected from the Side of a Magnet.

Dr. Kerr finds† that the plane of polarization of light is also rotated when the light is reflected from the *side* of a magnet.

Fig. 256 represents a plan of his apparatus.

A block of iron, AB, is laid on the poles of a horse-shoe magnet; L is the lamp, P a metal screen with a slit in it, C the point where reflection takes place, NN′ the Nicols, E the observer's eye.

* The phenomenon is certainly not an air-rotation, which until now has escaped notice. Not only do all the experiments negative this hypothesis, but in a direct observation which I have made I found that a magnet which will impress a double rotation of 7′ on light reflected from its pole, has no effect whatever upon light passed without reflection through perforated poles, though if the effect had been an air-rotation, it should have been in this case four times as much as before, or some 28′.

† Phil. Mag. 1878, i., p. 161.

It is found that the only positions of the Nicols which would give pure extinction are those where the principal section of the first is parallel or perpendicular to the plane of incidence.

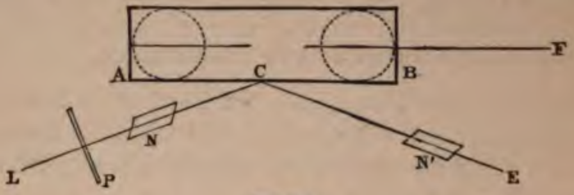


Fig. 256.

Dr. Kerr found that, when the magnet was excited, rotation took place in a direction whose relation to that of the magnetizing current depended on the angle and plane of incidence.

First Experiment.—Plane of polarization of first Nicol parallel to plane of incidence. The plane of polarization was rotated in the same direction as the magnetizing current.

By the "angle of incidence" is meant ½ angle LCE (fig. 256).

"The intensity of the optical effects of magnetization varies very noticeably with the angle of incidence. About incidence 85° the effects are very faint, but perfectly regular and much better than merely sensible; about incidence 75° they are more distinct and very sensibly stronger; about incidences 60° and 65° they are comparatively clear and strong, a good deal stronger than at 75°; about incidence 45° they are still pretty strong, but very sensibly fainter than at 60°; about incidence 30° they are again very faint, about the same as at 85°."

Second Experiment.—Plane of polarization of first Nicol perpendicular to the plane of incidence.

At about incidence 85° the effects were exactly the same as in the first experiment; then the effect diminished, and at about 75° it entirely disappeared; after 75° it began to re-appear, but the rotation was in the opposite direction; about incidence 60° the effect was comparatively clear and strong, though sensibly fainter than that obtained in the first experiment at the same incidence; about 30° it is faint, but still distinct and clearly stronger than the contrary effect obtained at 85°.

SUMMARY.

Thus, when the plane of polarization is parallel to the plane of

incidence, the rotation is always in the same direction as the magnetizing current for all incidences.

When it is perpendicular, the rotation is in the same direction as the magnetizing current for incidences between 85° and 75°, and in the opposite direction for incidences between 75° and 30°.

No sub-magnet was used in these experiments.

CHAPTER XLIX.

SELENIUM.

The only other direct action between electricity and light which remains to be mentioned is the alteration of the conducting power of selenium with light. Selenium is an exceedingly bad conductor, its resistance being about 3.8×10^{10} times that of copper.

It is found, however, that, when exposed to light, its resistance alters.

Prof. W. G. Adams has found* that *the change in the resistance of selenium is directly as the square root of the illuminating power.*

On May 18, 1876, Prof. W. G. Adams and Mr. R. E. Day communicated to the Royal Society a paper containing the results of a year's experimenting with selenium. The following extracts from that paper sum up what is now known on the subject:—

"It was observed that, with the same piece of selenium at the same temperature, the resistance diminished as the battery power was increased. Also it was found that the electrical resistance of the rod of selenium was different for currents going through it in different directions. Thus, if two platinum wires be melted into the selenium at two points, A and B, and the resistance of the selenium be balanced by the Wheatstone's bridge arrangement, the positive pole of the battery being connected to the electrode A, then, on reversing the current so that the negative pole of the battery was now connected to the electrode A, the numerical value of the balancing resistance required was always found to be different from that previously obtained.

"If the electrical conductivity of selenium followed the

* Proc. Roy. Soc., vol. xxv., 1876, p. 113.

ordinary law of metallic conduction, this would not be the case; and hence it seemed probable that a careful investigation of these points would lead to some important results.

"In the experiments recorded in this paper, the objects which the authors have had specially in view have been:—

"(1) To examine the character of the electrical conductivity of selenium when kept in the dark.

"(2) To determine whether light could actually generate an electric current in the selenium.

"Several pieces of selenium were prepared as follows:— A small piece varying from ¼ inch to 1 inch in length was broken off a stick of vitreous selenium. A platinum wire was then taken and bent round into a small ring at one end, and the remainder of the wire turned up at right angles to this ring. The rings of two such wires were then heated in the flame of a spirit lamp, and pressed into the ends of the little cylinder of selenium, thus forming platinum electrodes. The whole was then annealed.

"A few preliminary experiments were made to determine whether the change of resistance with change of direction of the current had any connection with the position of the selenium or the direction of the current with regard to the magnetic meridian. No such connection was found to exist.

"From the results obtained from a great many experiments made to determine the diminution of resistance with increased battery power, and the change of resistance with a change of the direction of the current, the following conclusions were drawn:—

"(1) That, on the whole, there is a general diminution of resistance in the selenium as the battery power is increased.

"(2) The first current through the selenium, if a strong one, causes a permanent *set* of the molecules, in consequence of which the passage of the current through the selenium during the remainder of the experiments is more resisted in that direction than it is when passing in the opposite direction.

"(3) The passage of the current in any direction produces a *set* of the molecules which facilitates the subsequent passage of a current in the opposite, but obstructs it in the same direction. Hence, when two currents are sent through successively, after a very small interval, in the same direction the resistance observed

in the second case even with the higher battery power is often equal to or greater than it was before.

"The results of these experiments seem to indicate that the conductivity of selenium is electrolytic. A number of experiments were undertaken in order to discover whether, after the passage of an electric current through a piece of selenium, any distinct evidence of polarization could be detected. It was then found that, after passing the current from a voltaic battery for some time through the selenium, and after having disengaged the electrodes from the battery, and connected them with a galvanometer, a current, in some cases of considerable intensity, in the opposite direction to that of the original battery current, passed through the galvanometer. This proved that the passage of the battery current sets up polarization in the selenium.

"All the results hitherto described were obtained with the selenium kept in the dark."

The authors then tried to discover whether, on exposing the selenium to light during the passage of the polarization current, any change in the intensity of that current would be produced. They found that in several cases there was a distinct change; in most instances the action of the light assisted the passage of the current; but in one case they found that the effect of light was not only to bring the deflection ot the galvanometer down to zero, but also to send it up considerably on the other side.

"Here there seemed to be a case of *light actually producing an electro-motive force* within the selenium, which in this case was opposed to and could overbalance the electro-motive force due to polarization.

"The question at once presented itself as to whether it would be possible to *start a current in the selenium merely by the action of light.* Accordingly, the same piece of selenium was connected directly with the galvanometer. While unexposed, there was no action whatever. On exposing the tube to the light of a candle, there was at once a strong deflection of the galvanometer needle. On screening off the light, the deflection at once came back to zero.

"This experiment was repeated in various ways and with light from different sources, the results clearly proving *that by the action of light alone we can start and maintain an electrical current in the selenium.*

"All the pieces of selenium hitherto used had repeatedly had electrical currents passing through them, and it therefore seemed desirable to examine the effect of exposure to light on pieces of selenium which had never before had an electrical current sent through them.

"Accordingly, three pieces were prepared as nearly alike as possible, and were annealed. Two of them were found on trial to be sensitive to light—that is to say, light impinging on them produced an electrical current. The third piece, however, showed no signs of sensitiveness. Hence it appears that three pieces which were made up from the same stick, which are of the same length, and were annealed at the same time, may, owing to some slight difference in their molecular condition, be very different as to their relative sensitiveness to the action of light.

"In the experiments by which the above results were obtained, the piece of selenium under examination had always been exposed as a whole to the influence of the light, so that it was not possible to tell whether any one part of a piece was more sensitive than any other."

In order to examine into this point more fully, the authors "used the lime-light, and then, by means of a lens, the light was brought to a focus on the particular portion of the selenium plate which was to be tested. A glass cell containing water, and having parallel sides, was interposed in the path of the beam, so as to assist in absorbing any obscure heat-rays.

"The result of these experiments proved conclusively the following points:—

"(1) That pieces of annealed selenium are in general sensitive to light, i.e. that under the action of light a difference of potential is developed between the molecules which under certain conditions can produce an electric current through the substance.

"(2) That the sensitiveness is different at different parts of the same piece.

"(3) That in general the direction of the current is from the less towards the more illuminated portion of the selenium, but that, owing to accidental differences in molecular arrangement, this direction is sometimes reversed.

"The currents produced in the selenium by the action of light do not resemble the thermo-electric currents due to heating of the junctions between the platinum electrode and the selenium;

for in many cases the current produced was most intense when the light was focussed on points of the selenium not coinciding with the junctions; also the current was produced suddenly on exposure; and, on shutting off the light, the needle *at once* fell to zero: the gradual action due to gradual cooling was entirely wanting.

"When the light fell upon a junction, the current passed from the selenium to the platinum through the junction, which is not in accordance with the place assigned to selenium in the thermo-electric series of metals.

"Experiments were next undertaken in order to examine what effect would be produced on the strength of a current which was passing through a piece of selenium in the dark when a beam of light was allowed to fall upon it.

"The results obtained from these experiments were as follows:—

"With pieces of selenium of low resistance, and with a weak current passing through them,—

"(1) When light falls on the end of the selenium at which the current from the positive pole of the battery is entering the metal, it *opposes* the passage of the current.

"(2) When light falls on the end of the selenium at which the current is leaving the metal, it *assists* the passage of the current.

"With pieces of selenium of a high resistance it was found that in all cases the action of light tended to facilitate the passage of the battery current, whichever was its direction.

"It was also found that in those pieces which appeared so little sensitive to light that no independent current was developed in them by exposure, yet, when a current due to an external electro-motive force was passing through them, the exposure to light facilitated the passage of the current.

"The results of the experiments described in this paper furnish a possible explanation of the character of the action which takes place when light falls upon a piece of selenium which is in a more or less perfect crystalline condition.

"When a stick of vitreous selenium has been heated to its point of softening, if it were possible to cool the whole equally and very slowly, then the whole of the molecules throughout its mass would be able to take up their natural crystalline position,

and the whole would then be in a perfectly crystalline state, and would conduct electricity and heat equally well throughout its mass. But from the nature of the process it is evident that the outer layers will cool the most rapidly, and we shall have, in passing from the outside to the centre, a series of strata in a more and more perfect crystalline condition.

"Light, as we know in the case of some bodies, tends to promote crystallization, and, when it falls on the surface of such a stick of selenium, probably tends to promote crystallization in the exterior layers, and therefore to produce a flow of energy from within outwards, which under certain circumstances appears, in the case of selenium, to produce an electric current.

"The crystallization produced in selenium by light may also account for the diminution in the resistance of the selenium when a current from a battery is passing through it, for, in changing to the crystalline state, selenium becomes a better conductor of electricity."

CHAPTER L.

CLERK MAXWELL'S ELECTRO-MAGNETIC THEORY OF LIGHT.

ELECTRIC induction is a strain of some kind; and, when electric induction passes through space in which there is not any ordinary matter, we agree to call the unknown something that fills the space and transmits the strain an "ether."

Light is a strain of some kind; and when light passes through space where there is not any ordinary matter, we agree to call the unknown something that fills the space and transmits the strain an "ether."

All men of science are agreed that light consists of vibrations of an ether or very thin fluid which fills all space, and probably permeates all bodies.

Prof. Clerk Maxwell's theory is briefly this :—

Electro-magnetic induction is propagated through space by strains or vibrations of the same ether which conveys the light vibrations, or, in other words, "light itself is an electro-magnetic disturbance."

Let us examine the evidence which causes us to believe that the luminiferous and the electro-magnetic ethers are one and the same.

The first point of resemblance between the modes of propagation of light and of electro-magnetic induction is that in both cases it can be shown mathematically that the disturbance is at right angles to the direction of propagation.

It is known that the waves of light take place in directions at right angles to the ray.

Prof. Clerk Maxwell has shown that the directions of both the magnetic and electric disturbances are also at right angles to the line of force.*

* They are also at right angles to each other.

Fig. 257 shows Prof. Maxwell's conception of a line of electric force.

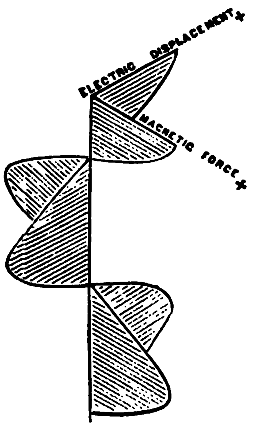


Fig. 257.

The vertical line is the direction of the force, and the magnetic and electric disturbances are at right angles to it.

Another argument in favour of the theory is that it gives a real mathematical reason for the fact that all good true conductors are exceedingly opaque. All metals, for instance, conduct, and are opaque. The conduction of electricity by transparent liquids takes place in a different manner from the conduction by metals, and does not affect the deduction, which can be shown mathematically to be a necessary consequence of the theory, namely, that all good true conductors must be opaque to light.*

But far more important evidence in favour of the view that the ethers are not two, but one, is obtained by comparing the velocities with which optical and electro-magnetic disturbances are propagated under different circumstances.

If it can be shown that the velocity of electro-magnetic induction is sensibly the same as that of light, not only in air and vacuum, but in all transparent bodies, we shall be quite sure that there are not two ethers, but one; for it would be unreasonable to suppose that the whole of every part of space is filled with two ethers which are identical in the only properties which we can examine, but which are yet different and not the same.

And, further, if the velocities nearly agree, but not quite, we must reserve our judgment; but we may be allowed to speculate on the possibility of the same ether vibrating somewhat differently when disturbed by electricity and by light.

Comparison of Velocities in Air and Vacuum.

The velocity of light has been measured experimentally in many ways.

* It must, however, be confessed that gold, silver, and platinum, when made into very thin plates, are not nearly so opaque as they should be according to the theory.

The most recent experiments are those made by Prof. Cornu,* in 1874, who found that in vacuo—

$$v = 3{\cdot}004 \times 10^{10} \text{ centims. per second.}$$

The following are the results of older observations :—

Fizeau	$3{\cdot}14 \times 10^{10}$
Astronomical observations .	$3{\cdot}08$ „
Foucault	$2{\cdot}98$ „
Mean . . .	$3{\cdot}06$ „

M. Cornu's experiments are, however, so greatly superior in accuracy to any of the older ones that we shall adopt his value, namely, 3·004.

Now the refractive index of air is

$$1{\cdot}000294.$$

The velocity of light in air is then :—

$$\frac{3{\cdot}004 \times 10^{10}}{1{\cdot}000294} = 3{\cdot}0031 \times 10^{10}$$

Now the mean value † of the most recent determinations of the ratio of electro-static and electro-magnetic units gives us for the velocity of electro-magnetic induction in air—

$$v = 2{\cdot}9857 \times 10^{10}$$

We may therefore say that *the velocities in air of light and of electro-magnetic induction are sensibly equal.*

Velocities in other Media.

The velocity of light in any medium of refractive index μ is—

$$\frac{\text{velocity in air}}{\mu}.$$

Prof. Clerk Maxwell has proved mathematically that the velocity of electro-magnetic induction in any medium is—

$$\frac{\text{velocity in air}}{\sqrt{K}}$$

where K is the specific inductive capacity for electro-static induction as defined in vol. i., page 69.

Now, if the velocity of light is equal to that of electro-magnetic induction in all transparent insulators, we should have,

* "Annales de l'Observatoire de Paris," 1876. "Mémoires," tom. xiii. p. A_1.

† Vol. ii. p. 202.

$$\frac{\text{velocity of light in air}}{\mu} = \frac{\text{velocity of electro-magnetic induction in air.}}{\sqrt{K}}$$

But we have shown that the velocities in air are equal, and hence, if the other velocities are equal, we must have—

$$\mu = \sqrt{K}.$$

We must note that Prof. Maxwell shows that among the values of μ we must select that which corresponds to waves of infinite wave length.*

GORDON'S EXPERIMENTS.

The following table compares the values of μ and $\sqrt{K}$ for various dielectrics as determined by the present writer (see vol. i, p. 118):—

Dielectric.	$\sqrt{K}$.	$\mu_{\lambda=\infty}$.	μ_D.	μ_{H_1}.	$\lambda_{\mu=\sqrt{K}}$
Double extra-dense flint glass . .	1·778	1·672	1·710	1·757	3·527, the wave length for N in ultra violet.
Extra-dense flint glass	1·747	1·620	1·650	1·688	2·862
Light flint glass .	1·734	1·555	1·574	1·601	
Hard crown glass .	1 763	1·504	1·517	1·533	
Paraffin . . .	1·4119	1·4220†	1·9		
Sulphur . . .	1·606		2·4		
Bisulphide of carbon .	1·345	..	1·611		
Common plate glass .	1·801	..	1·543		

* To determine the refractive index for waves of infinite length, we proceed as follows:—

We have the general equation

$$\mu = A + \frac{B}{\lambda^2} \quad . \quad . \quad . \quad (1)$$

To determine A, a determination of the values of μ for two rays of different wave lengths λ and λ' are necessary and sufficient, for we have

$$\mu\lambda^2 = A\lambda^2 + B$$
$$\mu'\lambda'^2 = A\lambda'^2 + B$$

Subtracting one equation from the other we eliminate B and obtain

$$A = \frac{\mu\lambda^2 - \mu'\lambda'^2}{\lambda^2 - \lambda'^2} \quad . \quad . \quad . \quad (2)$$

But from (1) when $\lambda = \infty$, $\mu = A$. Hence

$$\mu_{\lambda=\infty} = \frac{\mu\lambda^2 - \mu'\lambda'^2}{\lambda^2 - \lambda'^2} \quad . \quad . \quad . \quad (3)$$

—Phil. Trans., 1879. Part I. p. 441.

† Gladstone and Clerk Maxwell; Maxwell's "Electricity," § 789, vol. ii. p. 389. The melting point of my paraffin was 68° C., that of Dr. Gladstone's was less than 57° C.

The value of μ is given for the rays H_1, D, and for rays of infinite wave length. The last column shows for what wave length the refractive index would equal the square root of the specific inductive capacity.

Gibson and Barclay's Experiments.

Messrs. Gibson and Barclay found for paraffin (see vol. i., p. 86)

$$\sqrt{K} = 1\cdot405$$

which does not differ much from the value of μ given in the preceding table.

Boltzmann's Experiments.

We can either compare $\sqrt{K}$ with μ or K with μ^2.

In the comparison given by Prof. Boltzmann, the latter plan is adopted.

The following table, comparing the values of K and μ^2, is given by Prof. Boltzmann in his paper quoted in vol. i., page 87.

Dielectric.	K		μ^2
	From condenser method.	From attraction method.	
Sulphur . .	3·84	3·90	4·06
Paraffin . .	2·32	$\left\{\begin{matrix}2\cdot30\\2\cdot34\end{matrix}\right\}$	2·33
Resin . . .	2·55	2·48	2·38

Crystalline Sulphur.

In the paper quoted in vol. i., page 100, Prof. Boltzmann gives the following comparison of K and μ^2 along the three axes g, m, k of crystalline sulphur.

Dielectric.		K	μ^2
Sulphur .	g	4·773	4·596
	m	3·970	3·886
	k	3·811	3·591

Schiller's Experiments.

In the paper quoted in vol. i., page 103, Schiller gives the following comparison:—

Dielectric.	K		μ^2
	By slow method.	By oscillation method.	
Paraffin, slow cooled, white .	2·47	1·89 1·81	2·34
Quickly cooled, nearly transparent	1·92	—	2·19*
Brown India Rubber . .	2·34	2·12	2·25

Silow's Experiments.

In the paper quoted in vol. i., page 104, Silow finds for oil of turpentine—

$$\sqrt{K} = 1{\cdot}490. \quad \mu_{\lambda=\infty} = 1{\cdot}459.$$

Boltzmann's Comparison for Gases.

In the paper quoted in vol. i., page 123, Prof. Boltzmann gives the following comparison for gases.

The refractive index and the specific inductive capacity of vacuum are taken as unity.

Dielectric—Gases at 0°C. and 760 mm.	$\sqrt{K}$	μ
Air	1·000295	1·000294
Carbonic acid . .	1·000473	1·000449
Hydrogen . .	1·000132	1·000138
Carbonic oxide . .	1·000345	1·000340
Nitrous gas (N.O.) .	1·000497	1·000503
Olefiant gas . .	1·000656	1·000678
Marsh gas . .	1·000472	1·000443

* There is some confusion as to the arrangement of the numbers for paraffin in the table given in Schiller's paper.

General Conclusion.

An examination of the foregoing tables shows us that in some cases the velocities of light and of electro-magnetic induction are very nearly equal, but that in other cases there is a very wide difference.

On the whole a sufficiently close agreement has been observed to give us fair hope that some day the discrepancies may be explained and eliminated; and meanwhile the close agreement of the velocities of light and electro-magnetic induction in air and in gases, and the numerous direct relations which exist between light and electricity leave us but little doubt that they are very closely related, and that their effects are but two forms of that common energy whose nature is unknown, but which certainly underlies all physical phenomena.

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